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ARCSL-CR-77020

INVESTIGATION OF METHODS FOR DETECTION AND CONTROL OF PYROTECHNIC DUST FIRES AND EXPLOSIONS

by

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June 1977

NASA NATIONAL SPACE TECHNOLOGY LABORATORIES
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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
Chemical Systems Laboratory
Aberdeen Proving Ground, Maryland 21010

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The characteristics of sulfur dust fires and a method for control based on UV detection and high-pressure suppression were investigated. Sulfur/air dispersions were found to be subject to low-order detonations, accompanied by relatively slow-moving flame fronts. A high-pressure quency system, with a burst diaphragm triggered from a ultraviolet sensor, was found to control these reactions satisfactorily. Water was found to be less efficient as a suppressant than halogenated hydrocarbons.

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PREFACE

The investigation described in this report was authorized under PEMA 4932, Project 5761313, and MIPR 8166104601F4W5. It was performed at the NASA National Space Technology Laboratories (NSTL) for the Edgewood Arsenal Resident Laboratory (EARL) and NASA-NSTL by the General Electric Company under Contract No. NAS8-27750. Activity was initiated November 1975 and completed November 1976.

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Acknowledgement

The technical assistance of test support personnel of the NSTL Kellar Road Test Range is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF TABLES

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

INVESTIGATION OF METHODS FOR DETECTION AND CONTROL OF PYROTECHNIC DUST FIRES AND EXPLOSIONS

1.0 INTRODUCTION

1.1 Objective. The objectives of this study were (a) to investigate the nature of dust deflagrations that can occur in pyrotechnic manufacturing facilities, and (b) to evaluate a detector/suppression system for control of such reactions.

1.2 Authority. The work described in this report was authorized by MIPR 8166104601F4W5 from Edgewood Arsenal to the National Space Technology Laboratories.

1.3 Background. Previous results of the Edgewood Arsenal Pyrotechnic Hazards Evaluation Program have shown that fire is the most often encountered and most destructive hazard during production of pyrotechnic materials (1-5). In the usual plant environment, accidents that initiate from a small ignition source may propagate as a high-velocity fire storm through the production facility. When ignition occurs by dissipation of mechanical or electrical energy in a localized area below the surface of a bulk pyrotechnic mix, a transient pressure buildup may be occasioned by confinement of the reaction products within the body of material. As a result, extensive blowout of the mix can occur. Classic examples of this effect have been observed during recent simulated mixing operations using Jet Airmix or double cone blenders (3, 4). The flame front will then propagate through the dispersed material, ofttimes increasing velocity as the volume of burning material increases. As a result, the reaction may approach or exceed sonic velocity. This phenomenon is known as reaction runup, and has been investigated extensively by the Bureau of Mines for mine shaft scenarios (6, 7). Depending on the reaction velocity, normal sprinkler systems may not be effective unless the problem is detected early and unless the fireball can be confined to specific areas.

The potential effect of dust fires and explosions in U.S. Army munition plants has recently received increased emphasis due to the introduction of new material-handling techniques that involve automated-transfer equipment and, concomitantly, much larger quantities of material. Pneumatic conveying, large-scale blenders and continuous flow processing are being installed to replace conventional small-batch preparation of pyrotechnics. These new methods will reduce exposure of personnel to the hazards involved and through automated control can produce higher quality products at greatly increased output. However, the potential risk of damage to equipment and facilities must be determined, and measures for prevention of catastrophic accidents must be devised. Specifically, it is necessary to develop a system for early detection of a dust fire/explosion which simultaneously initiates some suppressive action that will minimize the hazard.

In reviewing available data on dust fires/explosions, it was obvious that all the conditions of environment and stimuli under which these problems occur in a factory are rarely known and difficult to simulate for repeatable laboratory studies. This project, therefore, was designed to move through a succession of steps to develop instrumentation, test methods, and experimental apparatus in which an actual dust fire/explosion could be initiated, propagated, measured, and suppressed. The basic requirement was to develop a working chamber which

could sustain a propagating dust fire/explosion of sufficient duration to allow measurements to be made of the reaction characteristics and to permit evaluation of the detection and suppression system.

2.0 EQUIPMENT AND APPARATUS

2.1 General Approach. Preliminary design criteria were obtained using a micro-scale dust gallery, consisting of a glass tube extension on a standard Hartmann apparatus. This dust dispersion system was used to determine the ability of the pneumatic system to disperse and sustain a dust column of sufficient length to make the apparatus useful in developing instrumentation and design data for a larger chamber. On the basis of the information gathered in these tests a second modification was made to the Hartmann apparatus, consisting of a steel tube chamber extension equipped with instrumentation outlets to measure the pressure wave and flame front characteristics of a sulfur dust fire/explosion. Sulfur was chosen as the fuel to be used for the test program because it is the most energetic fuel component in standard pyrotechnic smoke compositions. For this laboratory study, it was imperative to have a fuel which could be expected to react positively in repeated tests. From the preliminary test data, design criteria were developed for a full scale dust gallery and the reaction time requirement was established for a suppression system. During the design and fabrication of the larger gallery, a survey and evaluation were made of existing commercial extinguishing systems with specifications that would meet the reaction time requirements and would suppress a dust fire/explosion. A combination of two commercial systems was selected and used in this study. The system chosen used an ultraviolet flame sensor coupled with a pressurized deluge system. Two extinguishing agents were tested, a halogenated hydrocarbon and water. The apparatus and peripheral equipment used in this program thus consists of three major systems; (a) an extended tube Hartmann apparatus and a 10.4-meter dust gallery, (b) a fire detection and suppression system, and (c) the instrumentation and control system.

2.2 Extended Tube Hartmann Apparatus. The Hartmann apparatus was developed by the Bureau of Mines to evaluate dust hazard characteristics. In its original configuration, the chamber consisted of a 7-cm diameter steel tube 30.5 cm long that is mounted vertically on a dispersion cup and stand assembly, and connected to a pneumatic system for dust dispersal. The interior of the base assembly consists of the following:

(a) A dispersion cup receives the sample material.

(b) An adjustable compressed air deflector directs compressed air onto the sample to disperse the material in the chamber.

(c) An ignitor wire ignites the dust cloud when heated electrically.

The original apparatus was modified into two configurations for this program. Figure 1 shows the original base and pneumatic control system fitted with a 7.81-cm I.D., 1.52-meter long glass tube extension that was used to determine the ability of the system to form and sustain a dust column. Figures 2 and 3 show the steel tube extension added to the original chamber. Optical and pressure sensors were installed as shown to evaluate reaction characteristics prior to larger scale tests. Tests were conducted to determine the optimum air/sulfur density and ignition method which would produce the most repeatable propagating dust fire/explosion to establish design criteria for the full scale dust gallery.

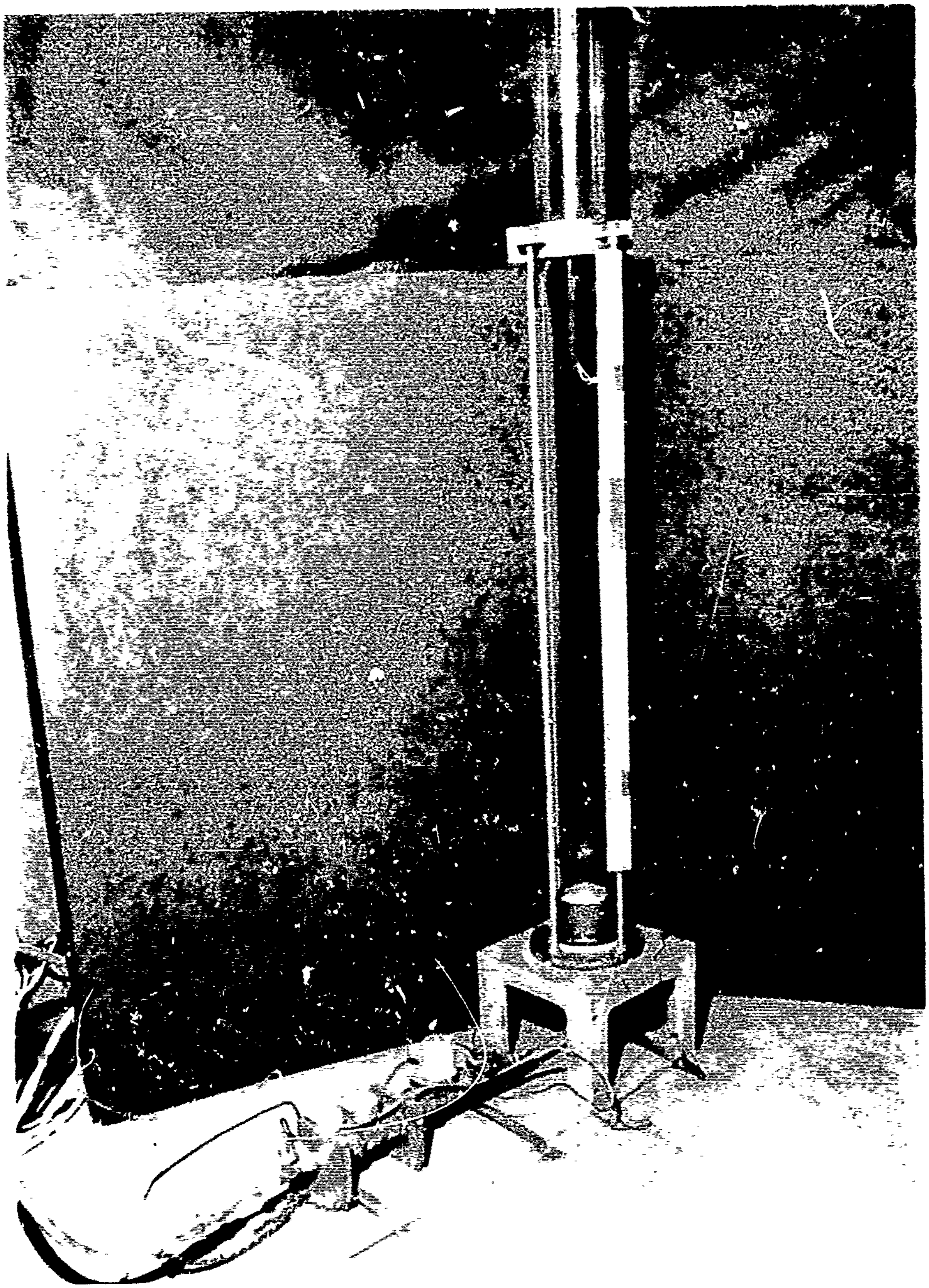


Figure 1. Glass Tube Extension to Hartmann Apparatus

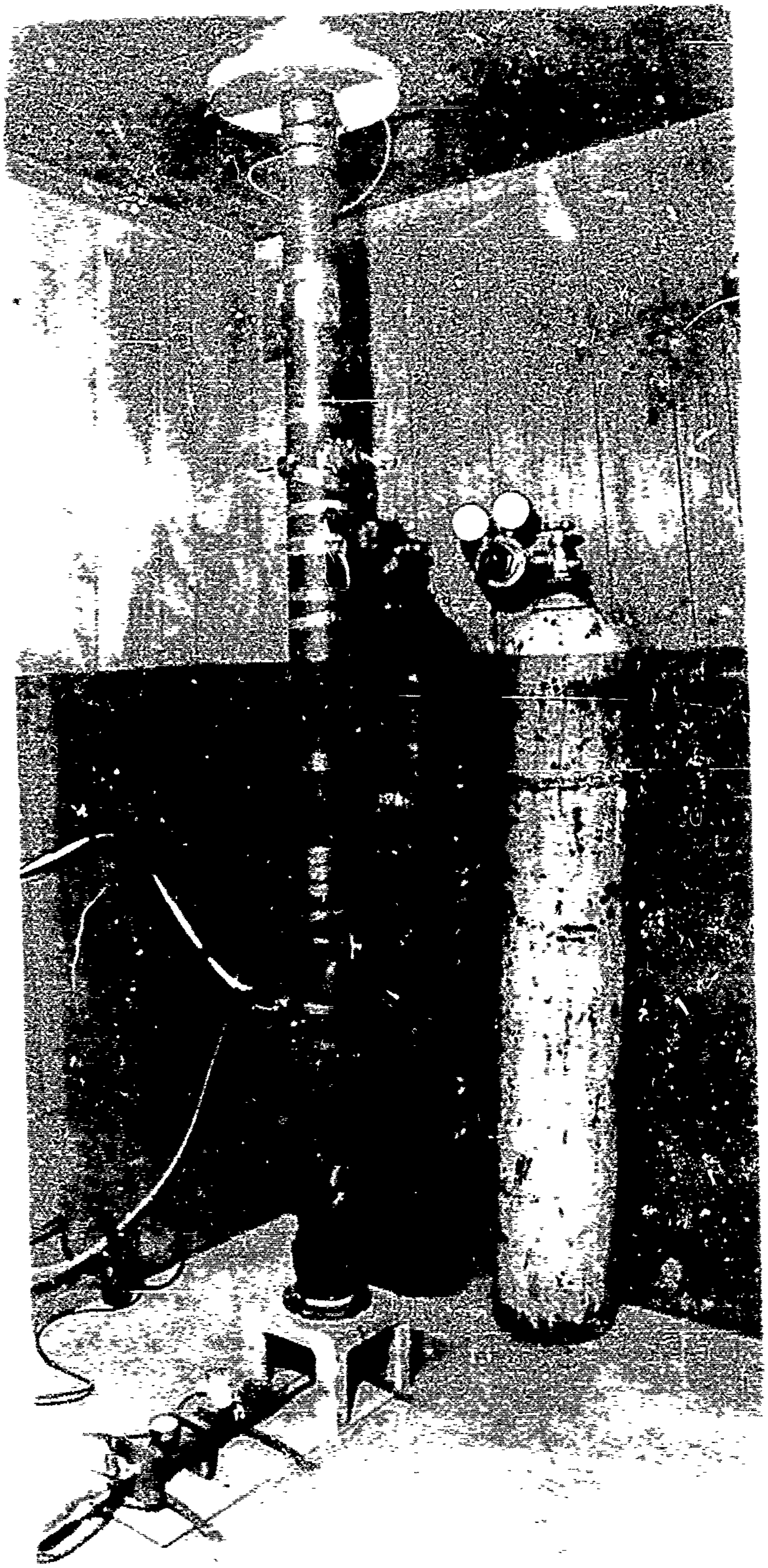


Figure 2. Steel Tube Extension to Hartmann Apparatus

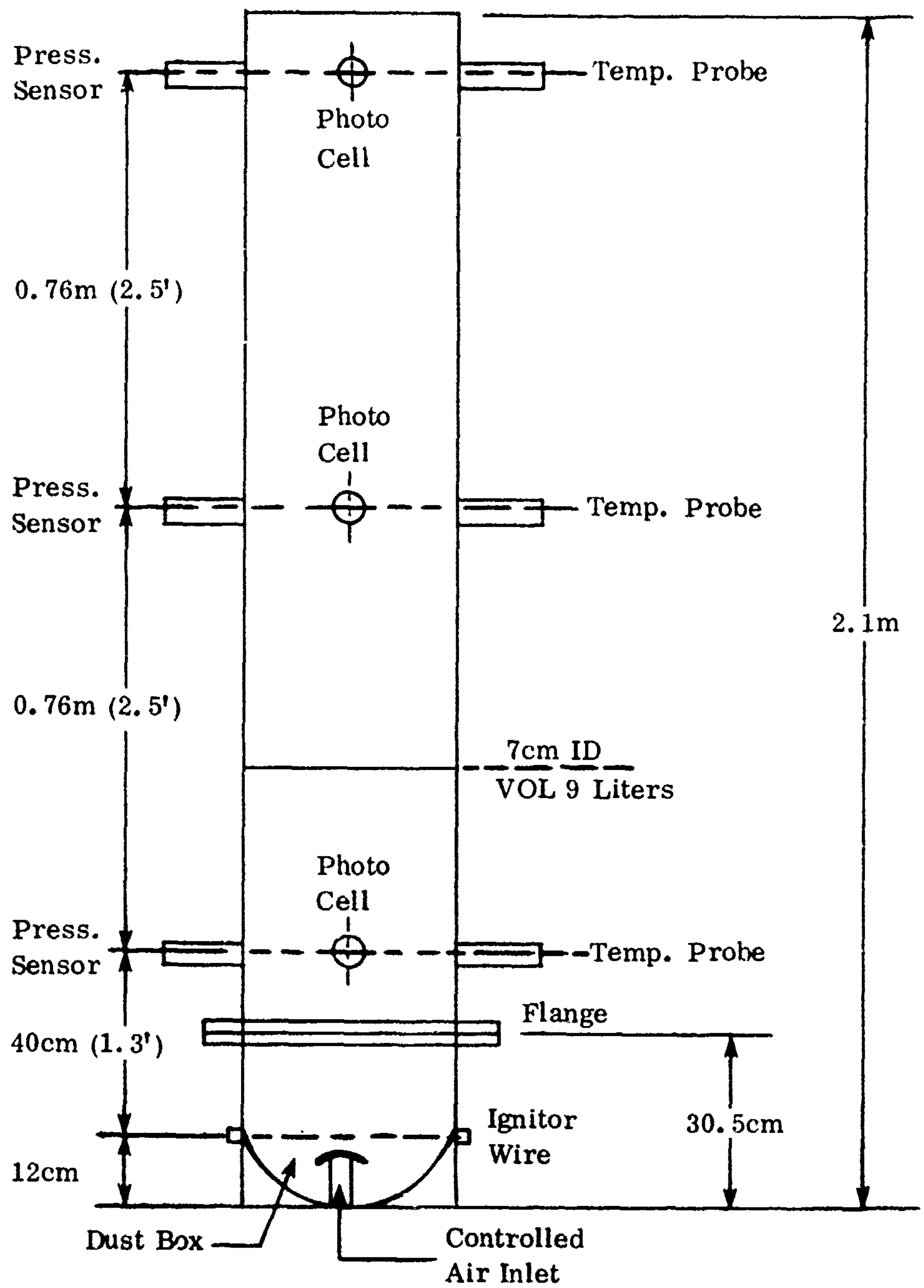


Figure 3. Extended Tube Hartmann Apparatus

In the second modification, an upper section consisting of a 7-cm I. D. steel tube 1.73 meters long was added to the original chamber. The appratus contained the following instrumentation:

(a) Three Susquehanna Instruments Model ST-2 pressure sensors were mounted 0.76 meters apart to evaluate pressure wave propagation.

(b) Three Monsanto Model MT-2 photo cells were mounted 0.76 meters apart to evaluate optical flame front propagation.

(c) Three iron-constantan thermocouple temperature probes were mounted 0.76 meters apart to measure arrival and temperature of the propagating flame front.

The pneumatic system outlined in figure 4 consisted of the following:

(a) "Missile grade" compressed air (dew point - 75°F, particulate contaminants less than 50 microns) was supplied from a standard gas cylinder.

(b) A standard two stage pressure regulator was installed on the air cylinder.

(c) A spring-loaded toggle valve was utilized to relieve pressure on the system by venting to the atmosphere.

(d) A 50 cm^3 reservoir was used to provide a single shot charge of compressed air.

(e) A full ported solenoid valve was utilized to release the compressed air charge to the chamber.

(f) A check valve connected downstream of the solenoid valve was used to prevent pressure relief and escape of combustion products back through the system.

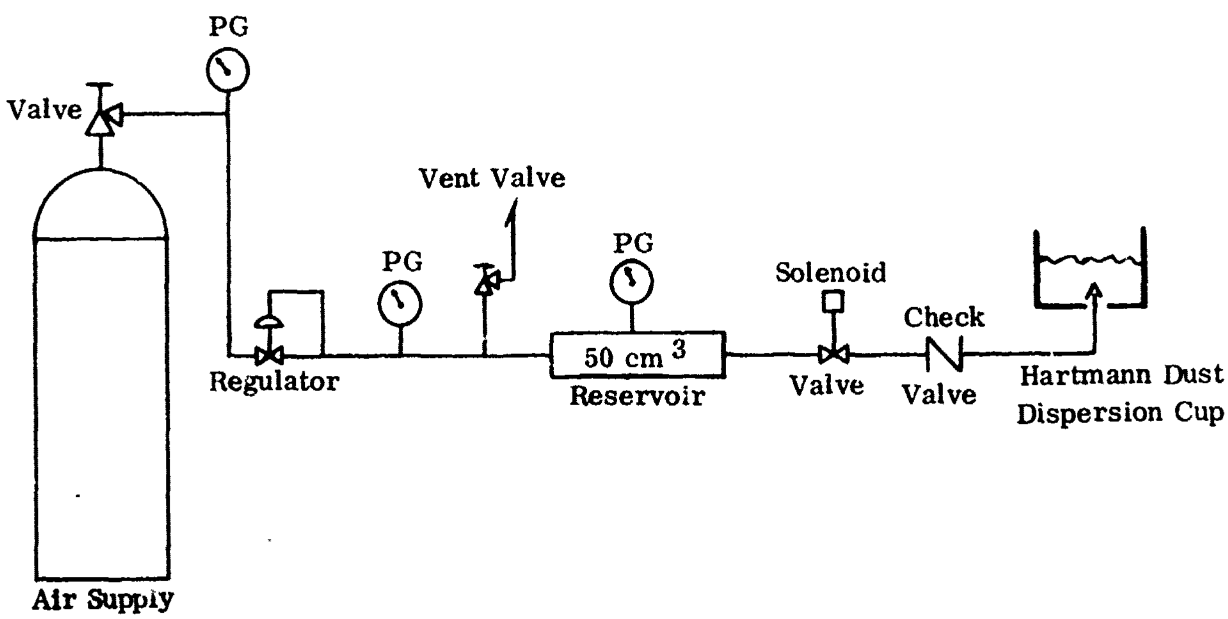


Figure 4. Hartmann Apparatus Pneumatic System

Ignition of the dust cloud was accomplished by one of the following electrical-power system:

(a) A continuous spark discharge unit, consisting of a capacitive discharge ignition system and an automotive ignition coil, was connected to spark gap electrodes. The pulse rate was 550 hertz, producing an average power of approximately 24 watts and spark energy of 23 millijoules.

(b) A 120-volt AC power source was connected to a short length of 0.10-cm-diamet stainless steel wire.

The instrumentation and control equipment used for the extended tube Hartmann test is shov in figures 5 and 6. The following is a list of the test equipment utilized:

ITEM	MANUFACTURER	MODEL
Power supply	Trygon	R.S. 4010
Pulse generator	Hewlett Packard	214A
Solenoid power supply	S.O.S. Photo-Cine Optics	BH
Control and capacitive discharge ignition	Custom built	
AC hot-wire ignition control	Custom built	

2.3 <u>10.36 Meter Test Chamber</u>. A schematic representation of the test chamber, dust dispersion system and the suppression system is shown in figure 7. Figures 8 through 15 show additional views of the systems and components. The test chamber is a rectangular box, 10.36 meters (34 feet) long by 0.46 meters (1.5 feet) in cross section, of plywood and Plexiglas construction. It is closed on one end, top, bottom and back with 1.9-cm plywood which is lined on the interior with galvanized sheet metal. The top was hinged in 1.2-mete sections to allow access to the dust nozzles and instrumentation sensors. Except for one plywood panel at the fire ignition end, the front was closed with 0.64-cm-thick Plexiglas sheet to facilitate observation of the reaction using high speed photography. The end throu which the extinguisher nozzle protrudes is enclosed with 0.13-mm plastic sheet. The chan ber is equipped with 17 combination dust-holder-distribution nozzles. The nozzles protrud through the bottom of the chamber to a height of 15.2 cm and are spaced 0.61 meters apart along the center line of the chamber. The nozzles are constructed of 2.54-cm schedule-40 pipe 12.7 cm long with an inverted cone mounted above the nozzle exit to aid in dispersal of the dust. The base of each nozzle was equipped with a plastic ring which held a tissue paper diaphragm to retain the dust prior to dispersal. Each nozzle has a capacity of 50 grams of sulfur, providing a total capacity of 850 grams used in each test.

The dust distribution nozzles, except for the one located in the center of the chamber, are connected in pairs to a 10.1-cm schedule-40 steel pipe manifold 9.75-meters long. O end has a 1.27-cm valve which isolates the manifold from an auxiliary air supply bottle. Compressed air at a manifold pressure of 758 kPa (110 psi) is used for forced distribution of the sulfur dust from the holder distribution nozzles into the chamber. Control of gas flo to each pair of nozzles is accomplished by use of a 2.54-cm full-ported solenoid valve and

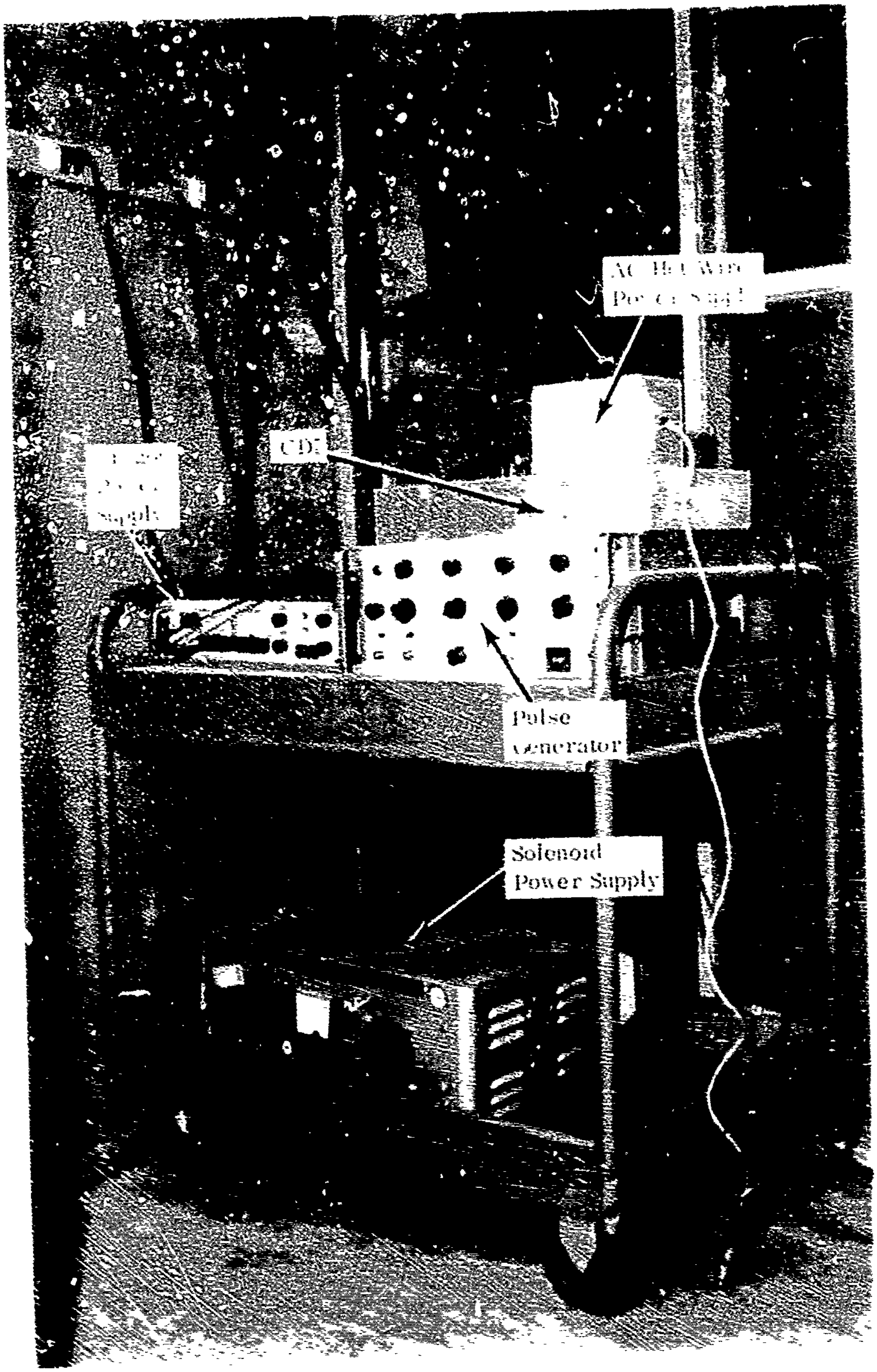


Figure 5. Hartmann Apparatus Instrumentation System.

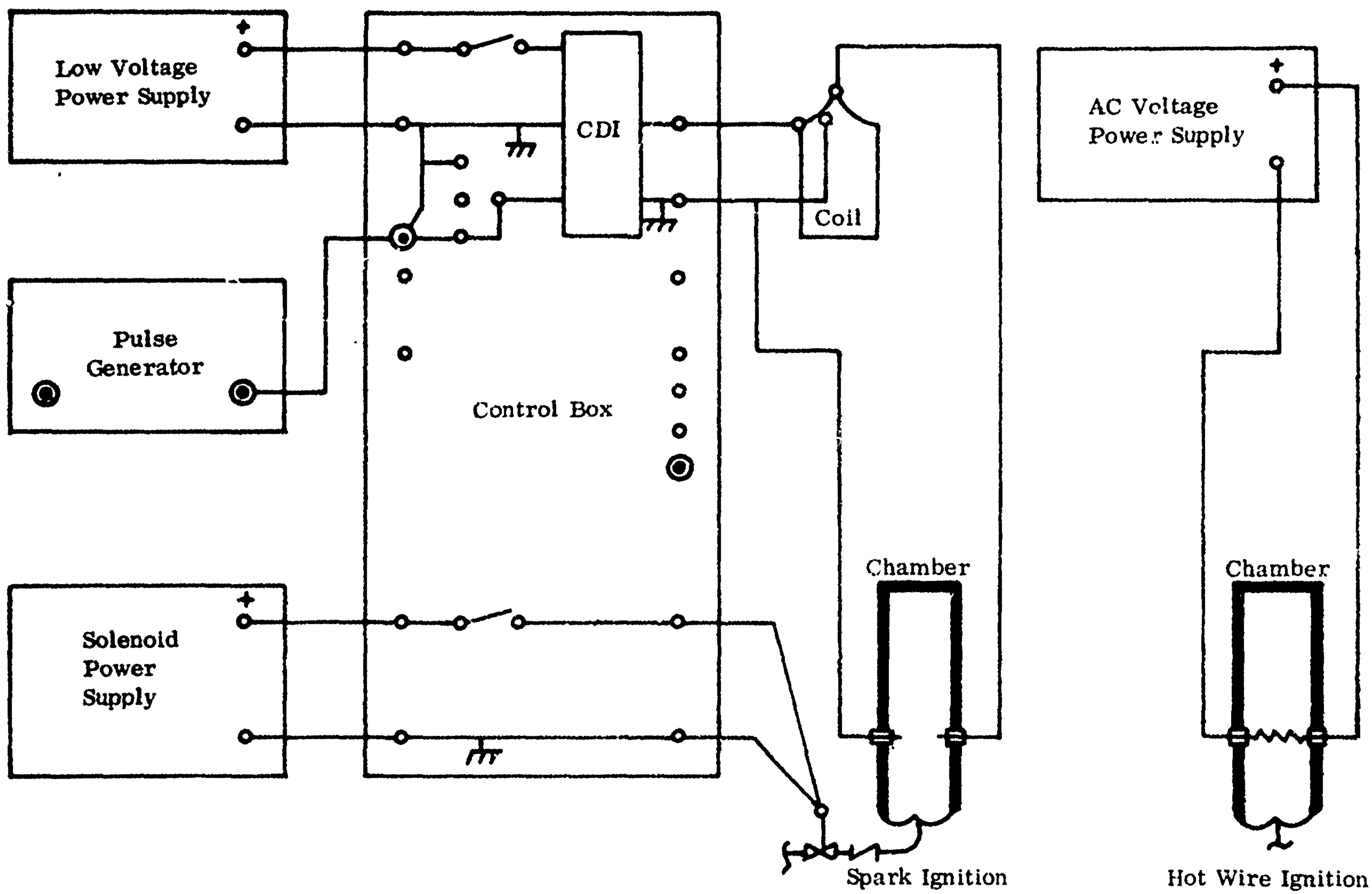


Figure 6. Hartmann Apparatus Electrical Control

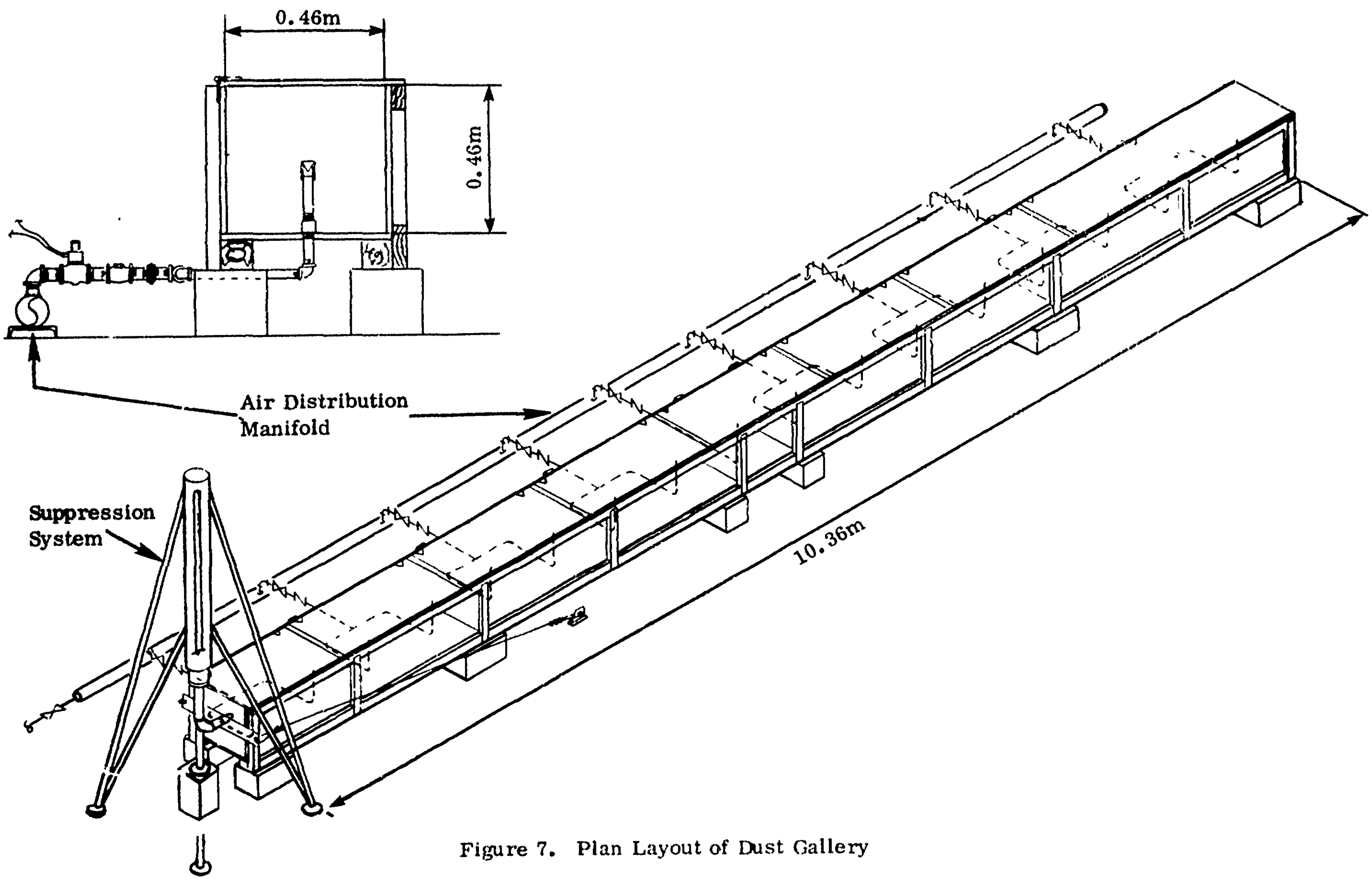


Figure 7. Plan Layout of Dust Gallery

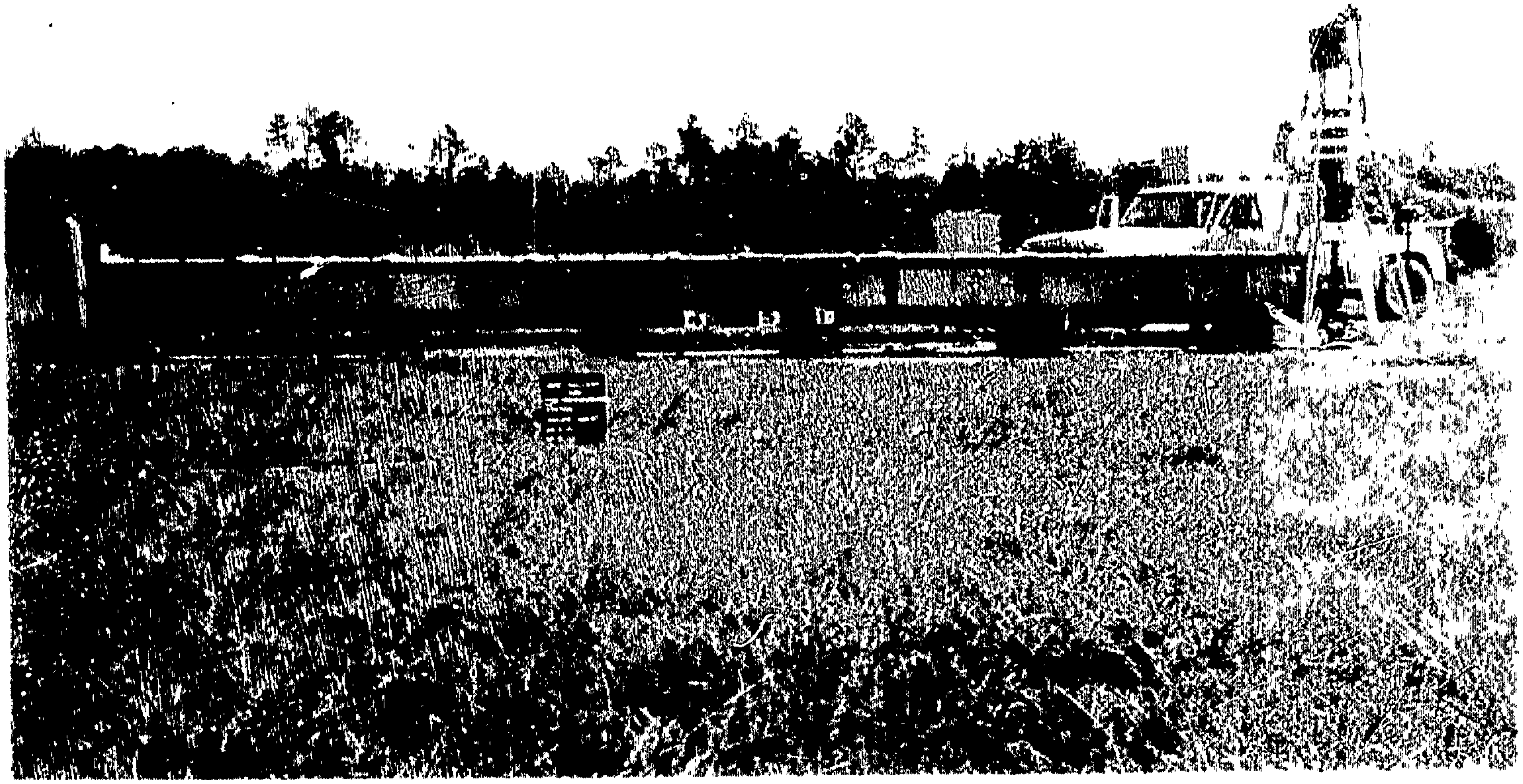


Figure 8. Dust Gallery, Front View

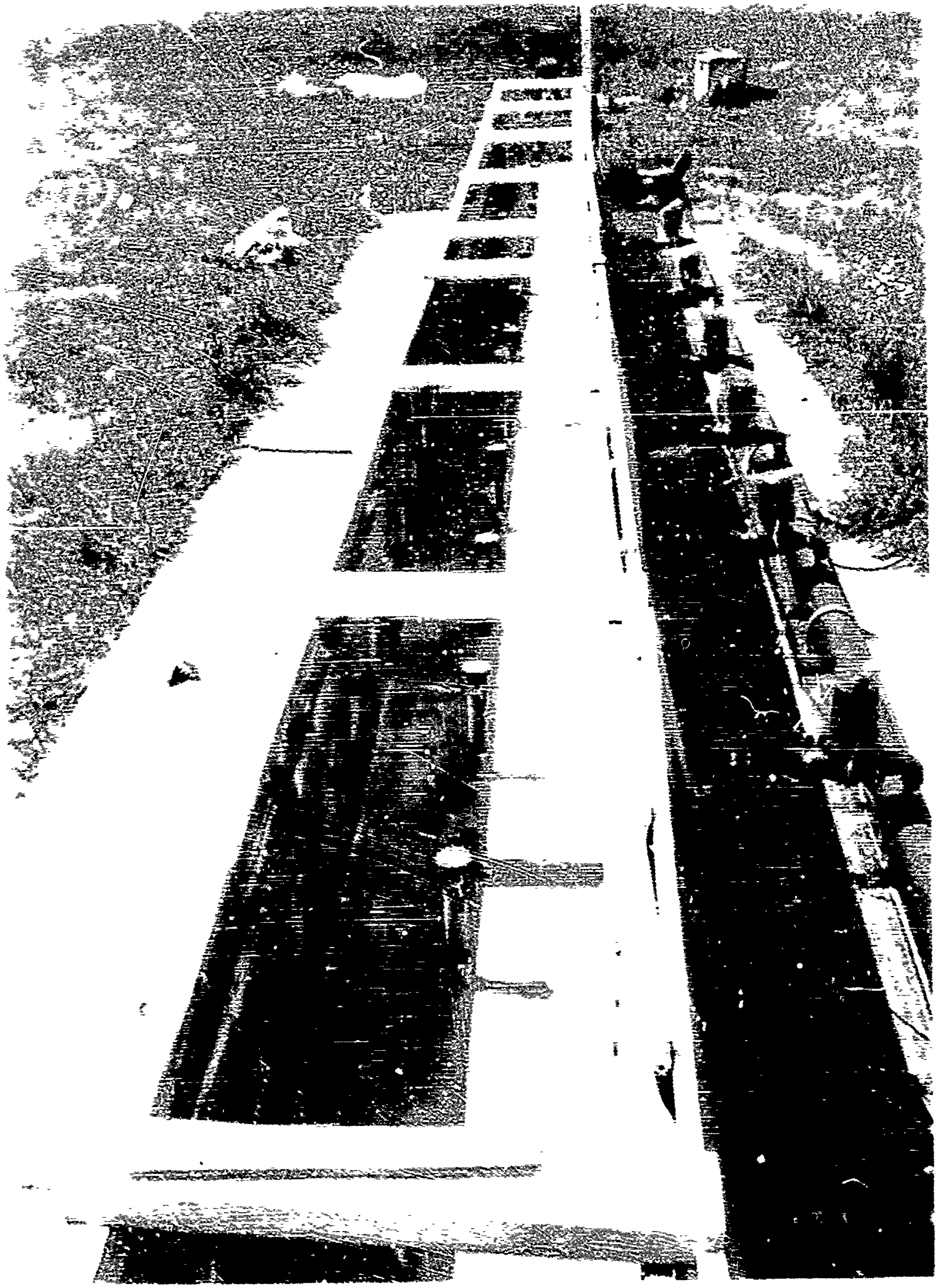


Figure 9. Interior View of Dust Gallery

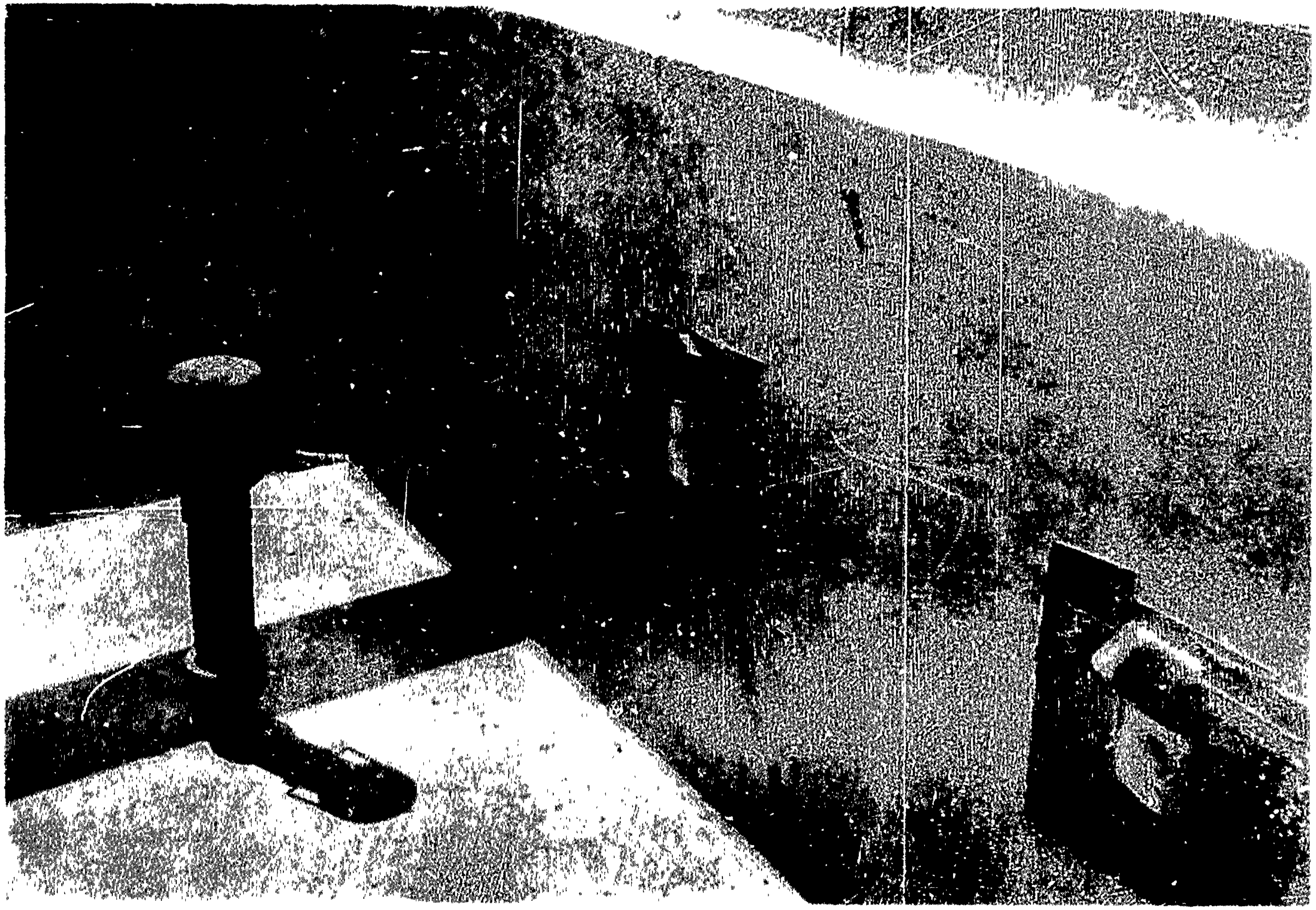


Figure 10. Dust Holder/Distribution Nozzle

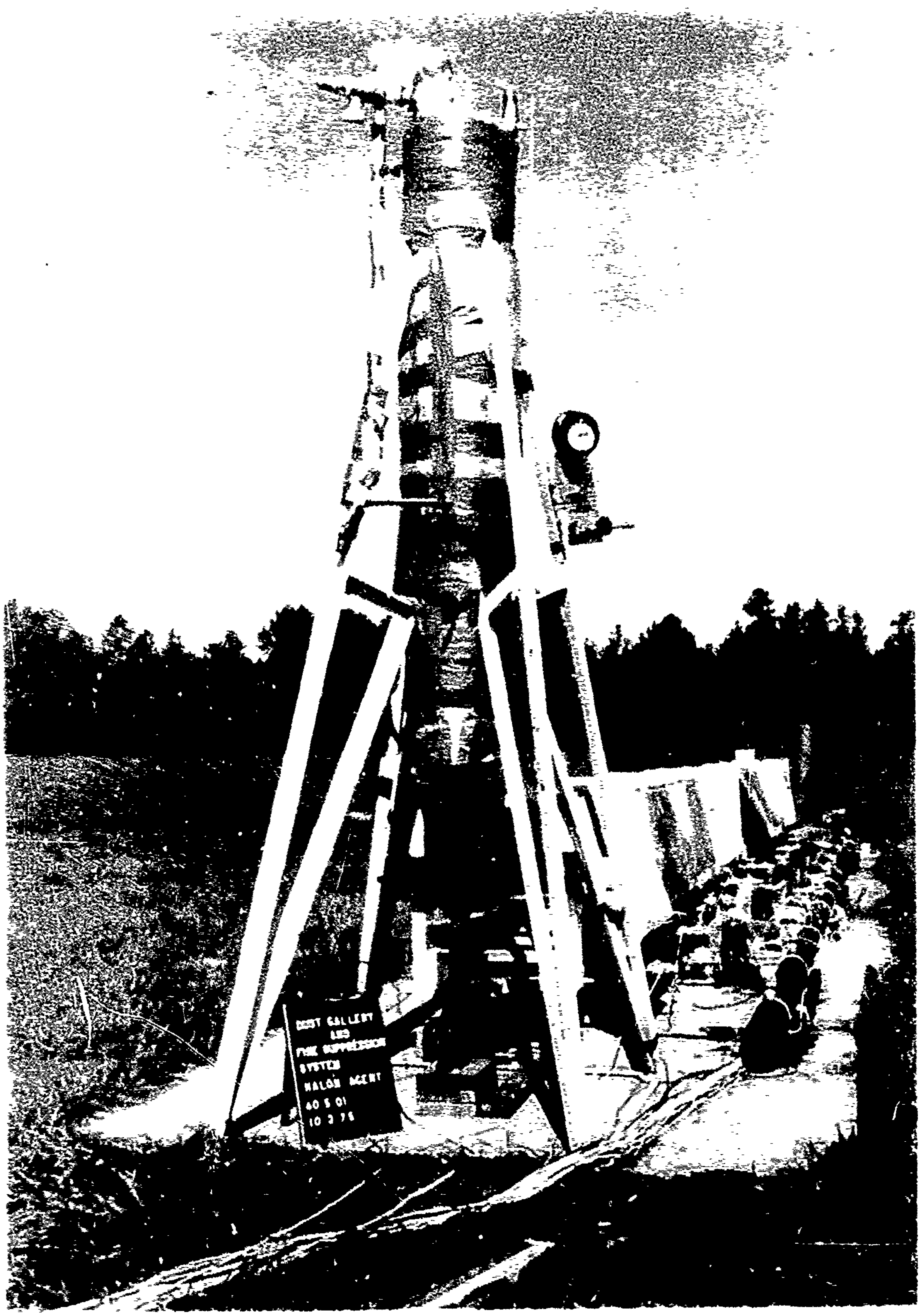


Figure 11. Dust Gallery Suppression System

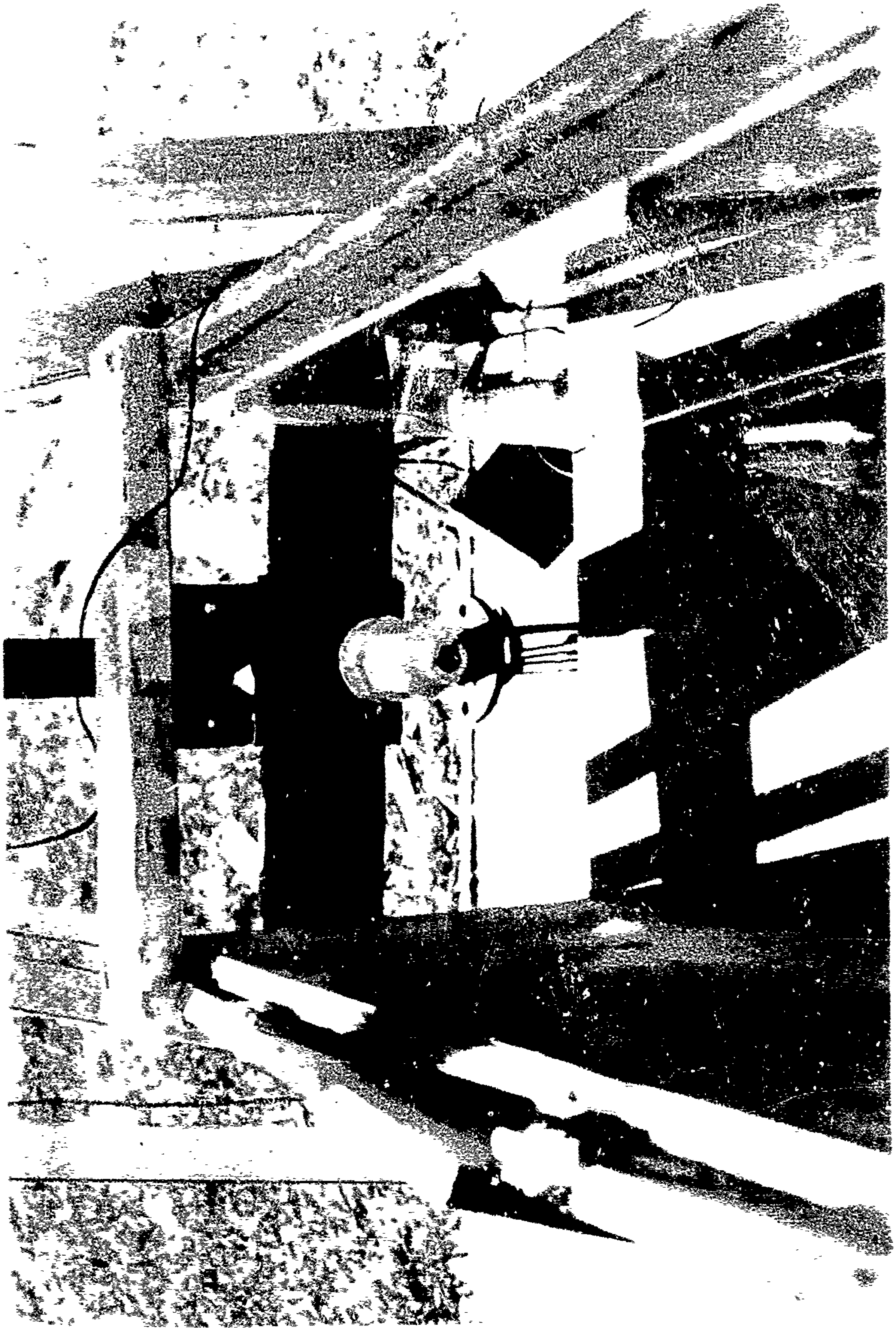


Figure 12. Extinguisher Nozzle

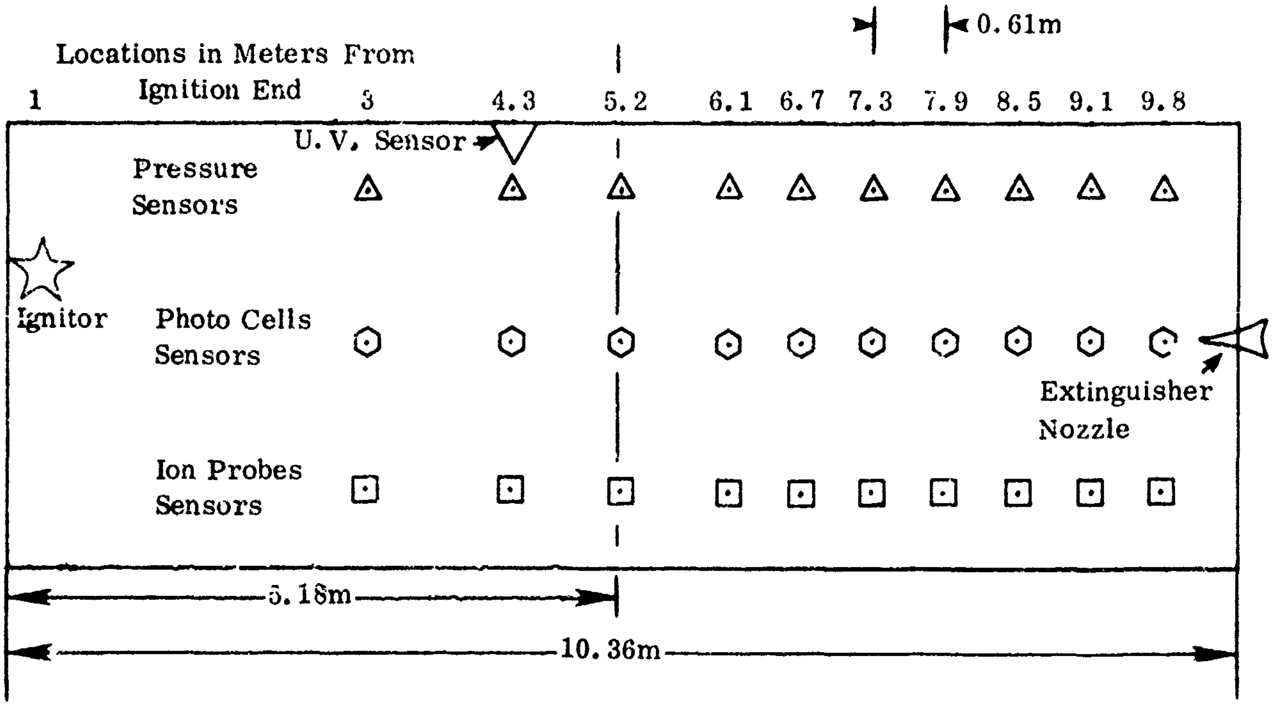


Figure 13. Sensor Locations in 10.36 Meter Test Chamber

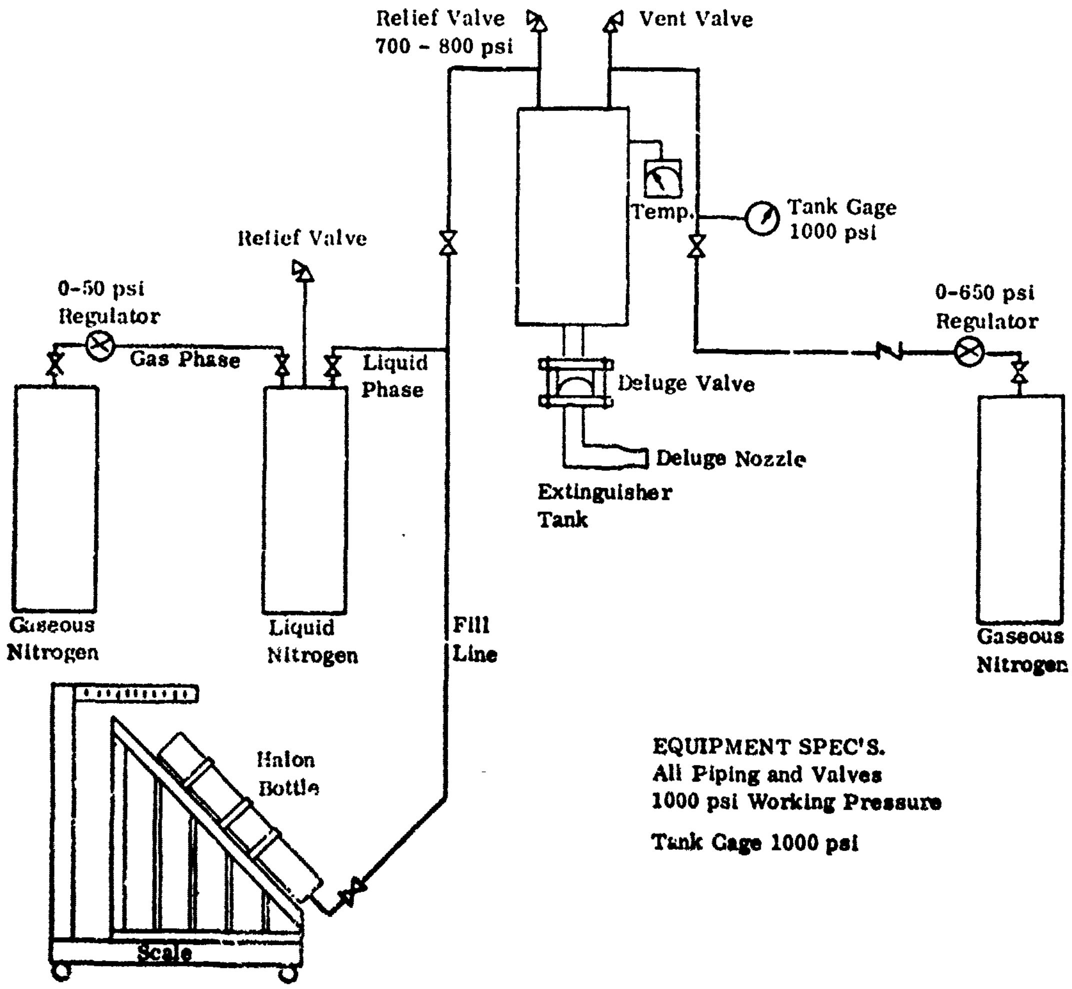


Figure 14. Halon Loading System

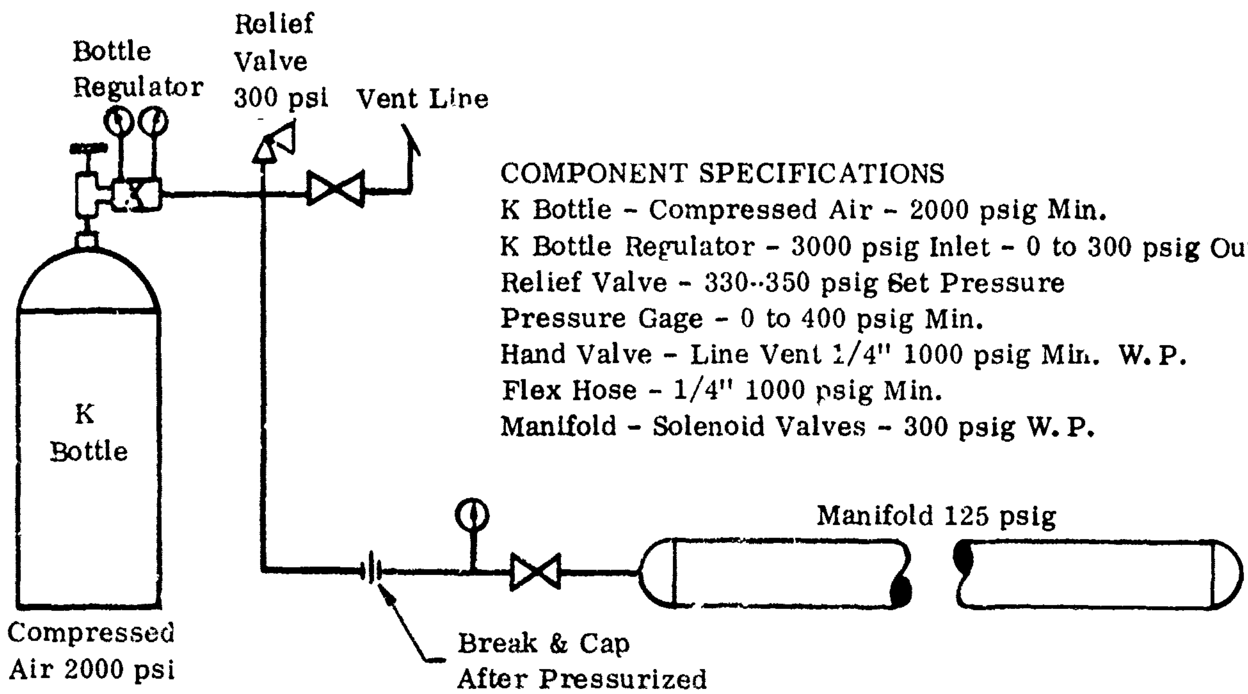


Figure 15. Gas Manifold Hook Up

valve to prevent back flow of pressure from the chamber during firing. The control for the nine air distribution valves is through an electrical-switching apparatus located near the chamber. Each valve can be controlled individually from this control box for checkout, and a sequencer triggers all the valves simultaneously during tests. This control system also contains a delay relay to provide a 2-second delay in valve activation after initiation of the igniter.

The test chamber is instrumented to measure the pressure wave and flame front velocity by use of transducers mounted on the back vertical face of the chamber, as shown in figure 13. The sensors were shifted among the locations noted for some tests to provide better coverage in the area where fire suppression was anticipated. The pressure and optical sensors used were identical to those described above. In addition, ion probes were used to measure the flame front arrival time at each location. The ion probes were developed locally and consisted of two bare wire electrodes spaced 0.1 mm apart with an impressed voltage of 200 volts. The probes are designed to discharge when the flame front produces an ionized atmosphere between the electrodes. During some tests, passive sensors (cotton balls) were installed along the gallery to indicate the limit of flame propagation. Photographic coverage for each test was provided by a Hulcher Model-40 70-mm sequencing camera operated at 20 pictures per second, and by a Hycam Model-41.004 16-mm unit operated at 1500 frames per second.

In all tests conducted with the suppression system, a single 40-mm M-43A1 red signal flare was used as the ignition source. The flare was removed from the shell casing and mounted in a trough made of 2.54-cm angle iron. The flare was installed 0.305 meters from one end of the test chamber and was ignited with an electric match attached to the fuse. The flare produced a fireball 0.61 meters in diameter and lasted for approximately 9 seconds.

Time zero (t_o) was established by ignition of the flare, and the dust dispersion system was triggered at t_o +2 seconds. A breakwire installed across one dust nozzle indicated arrival of dust in the chamber and a breakwire across the extinguisher nozzle indicated injection of the suppressive agent into the chamber.

2.4 Suppression System. The extinguisher tank is a 76-liter stainless steel cylinder with a working pressure of 13790 kPa (2000 psi), and contains the agents being evaluated for the suppression of dust fires/explosions in the test chamber. It is equipped with an extinguisher agent loading system, a pressurization system, and a system for expelling the contents of the tank into the test chamber. The tank is mounted at the end of the dust gallery opposite from the ignition source with the extinguisher nozzle protruding 0.305 meters into the chamber, see figure 13. The tank was insulated with aluminum backed fiberglass to facilitate cooling of the tank prior to loading. Figure 14 shows a schematic of the suppression system and the method used for loading and pressurizing the system.

A 114 liter liquid nitrogen (LN_2) dewar is used to precool the extinguisher tank prior to loading the Halon 1301 extinguishing agent. It is a standard LN_2 dewar with both liquid and gaseous phase control valves. Two pressurized bottles containing gaseous nitrogen (GN_2) at 13,790 kPa (2000 psig) are equipped with regulators and are used in conjunction with the suppression system. One is used to pressurize the LN_2 dewar during the tank precool operation, and the other was used to pressurize the extinguisher tank prior to testing. In addition, a standard compressed air bottle equipped with a regulator is used to pressurize the dust distribution manifold, as shown in figure 15.

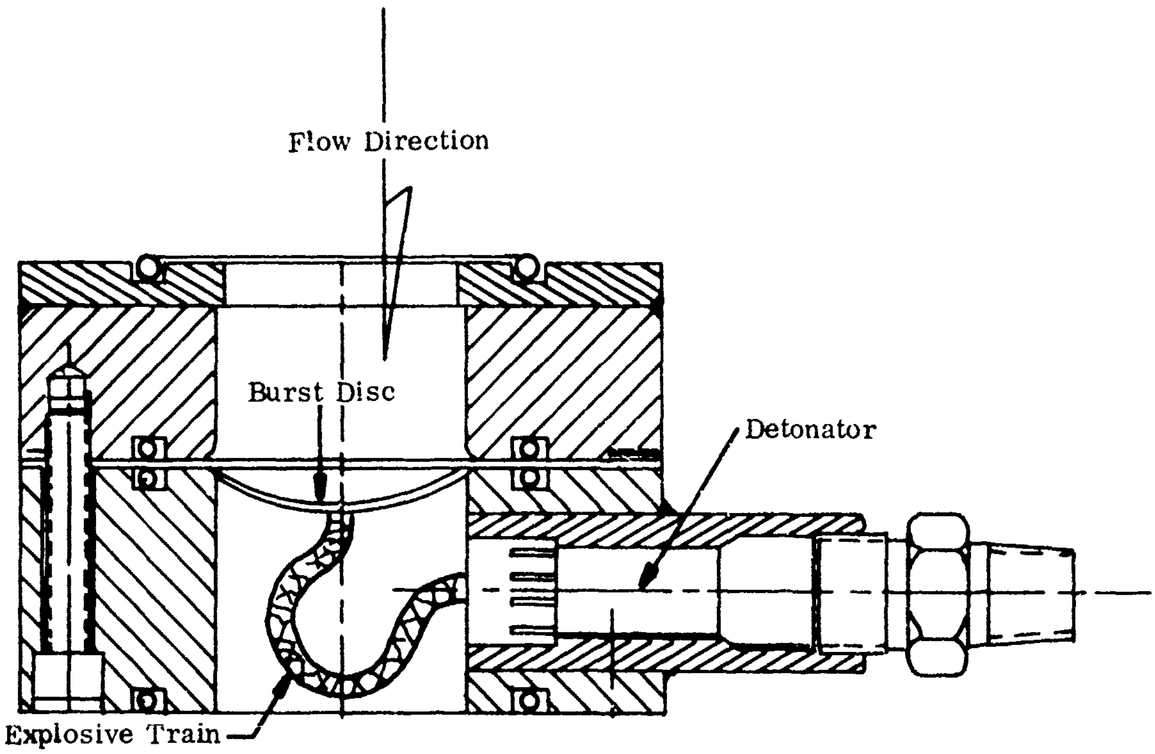
The extinguisher tank deluge valve is a Fike Model A-10 explosive burst diaphragm device, see figures 16 and 17. The valve is mounted on the outlet side of the tank and is composed of a split flange assembly for holding the rupture disc and the detonator assembly. The detonator is actuated by a signal from the UV controller. The detonator ignites the explosive train which breaks the rupture disc along prescored lines allowing the tank media to flow into the chamber. Tests were performed with the detonator in both downstream and upstream positions.

2.5 Ultraviolet Detector and Controller. The ultraviolet sensor and controller employed were Detector Electronics Corporation Models DE-C7050A and DE-R7300A. The controller is in modular form and consists of electronic circuitry for processing the detector signal plus several switching relays. The detector uses a Geiger-Mueller type tube designed to detect radiation in wavelengths from 185 to 245 nanometers. The tube is insensitive to UV radiation from the sun (at the earth's surface) or from artificial lighting. When the detector tube senses radiation of proper wavelength, a voltage pulse is transmitted to the controller which then energizes the deluge valve detonator. Power is supplied to the detector and associated circuitry by the Fike Metal Products Model IN40-004 24 volt DC power supply.

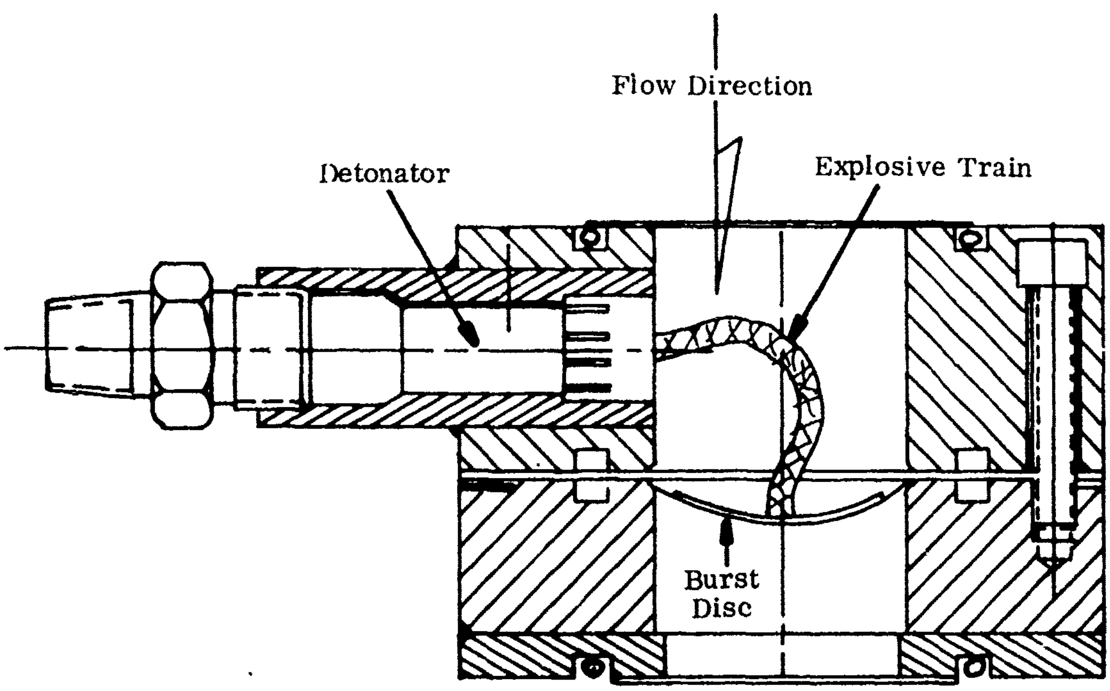
The electrical system wiring connection diagram and a block diagram showing interconnection of the units described in the above paragraphs are shown in Figures 18 and 19.

3.0 EXPERIMENTAL PROCEDURES

3.1 Sample Preparation. The following sample preparation procedure was used for all tests conducted with the Hartmann apparatus and with the large dust gallery:



DETONATOR DOWNSTREAM



DETONATOR UPSTREAM

Figure 16. Burst Diaphragm Assembly

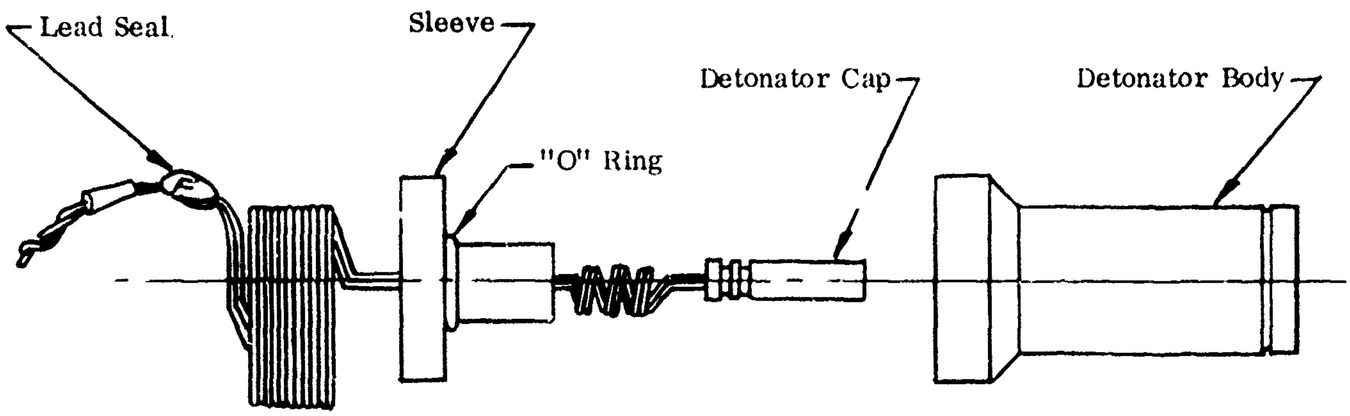


Figure 17. Detonator Assembly

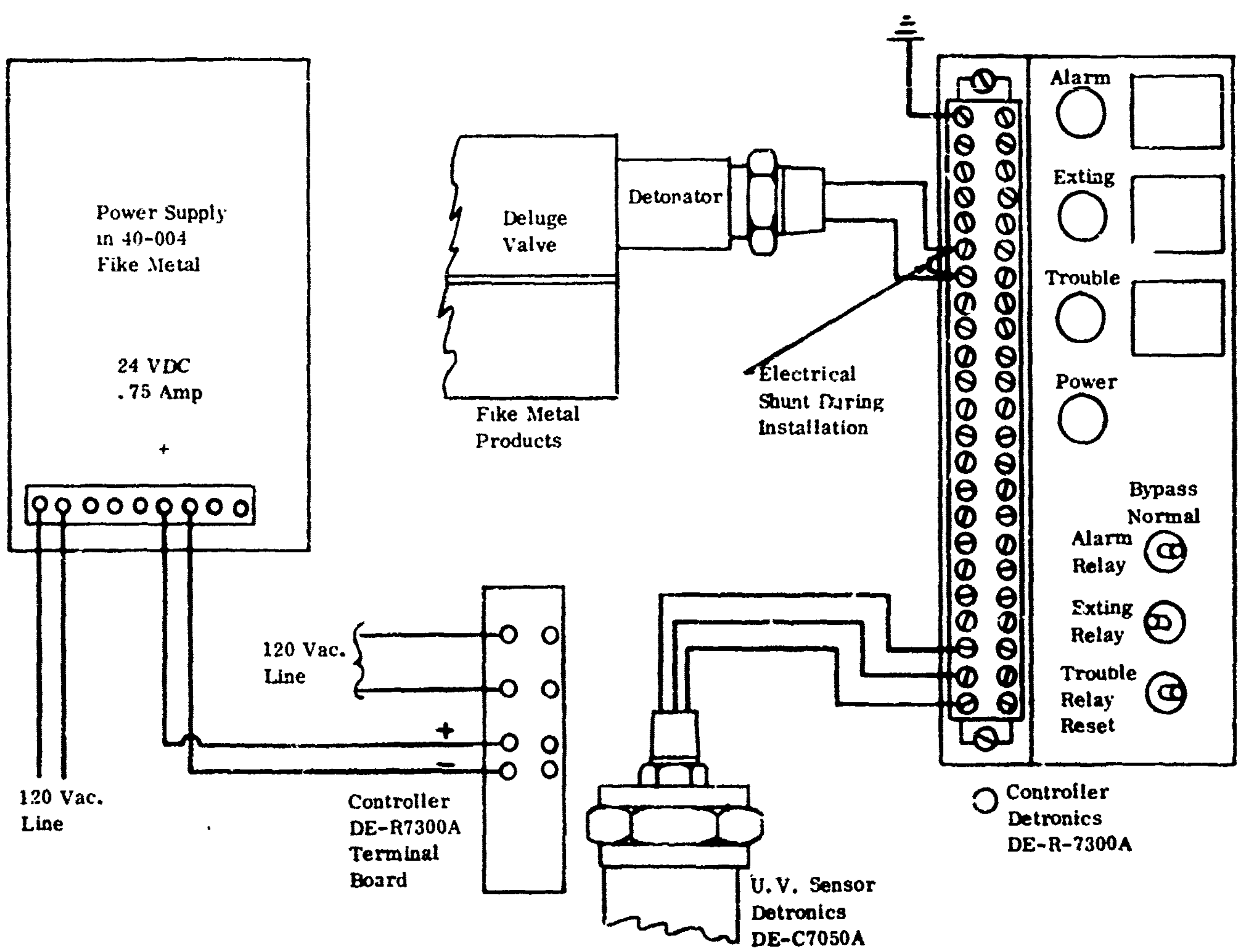


Figure 18. Extinguisher Tank Deluge Valve Control

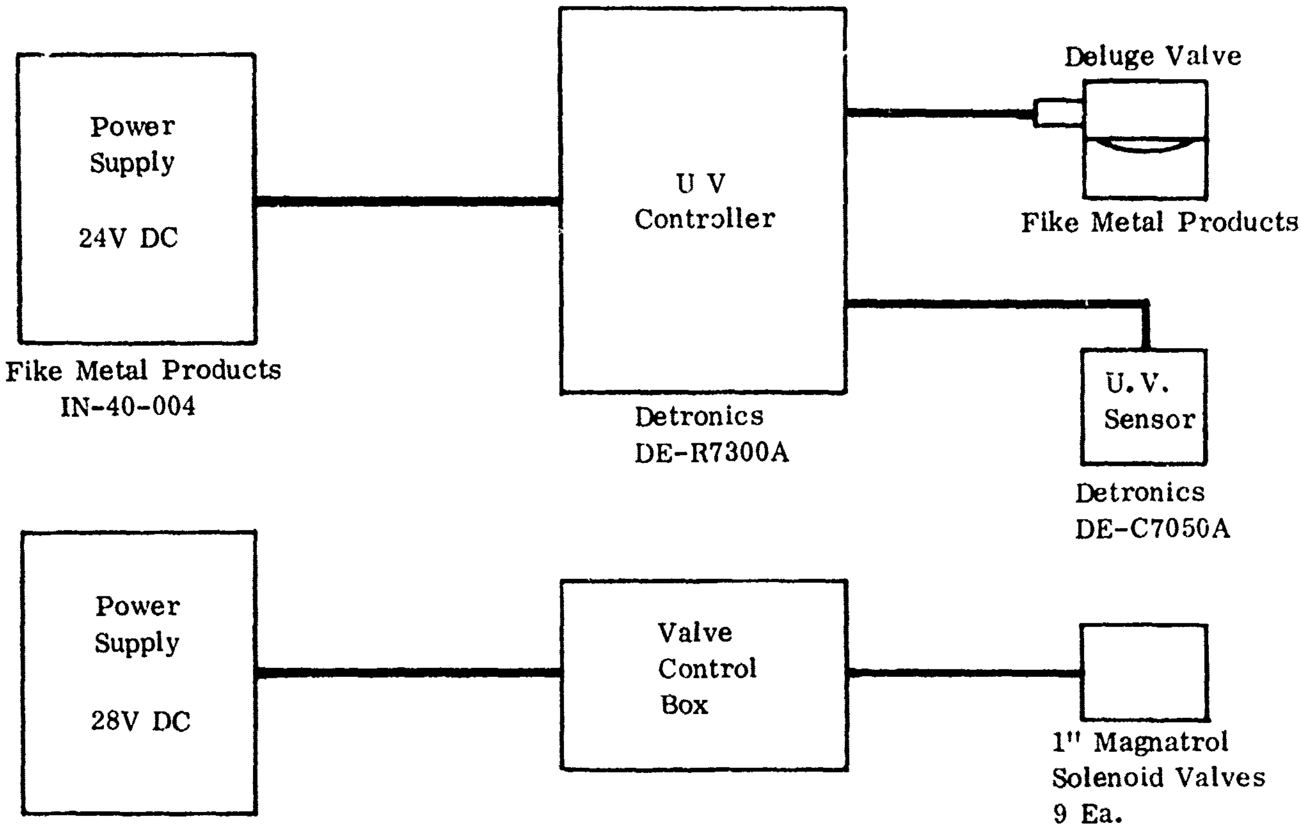


Figure 19. Electrical System Block Diagram

(a) All sample material was sieved through a No. 200 (U.S. Standard series) screen prior to drying and testing, to minimize particle size variation.

(b) The sample material was dried in an oven for 24 hours at 75°C.

(c) The sample material, after drying, was kept in a desiccator until needed.

(d) Samples were weighed to within ± 0.5 mg on a precision analytical balance before placement in the chamber or in the dust gallery dispersion tubes.

3.2 Glass Tube Hartmann Apparatus. A weighed quantity of material was placed in the dust dispersion cup. The pressure regulator was set to the desired pressure to allow charging of the accumulator for pulsed air discharge, or continuous flow from the pressure regulator through the accumulator was used during some of the tests. The sample was dispersed by opening the solenoid valve. Since these tests were only used to determine operating conditions required for the modified apparatus, visual observation could be used to determine the system performance level. A well dispersed cloud that completely filled the tube in one to two seconds was considered a satisfactory test. The gas dispersal pressure, height of dust in the tube, and the time required for maximum height were recorded.

3.3 Steel Tube Hartmann Modification. A selected, weighed quantity of material was placed in the dust dispersion cup, then the steel tube was connected to the base. The ignition source leads were connected to the spark gap or hot wire electrodes. The pressure

regulator was adjusted to the desired pressure and the control valve was opened. Power was applied to the ignition system, with simultaneous opening of the solenoid valve to disperse the dust. Evidence of propagation was determined by visual observation with a mirror mounted above the steel tube chamber exit. Timing of events was made relative to the application of power to the igniter. Measurements were recorded of the arrival time and magnitude of the pressure wave at each pressure transducer, time of arrival of the flame at each optical sensor, and time of arrival of the flame at each thermocouple sensor.

3.4 Dust Gallery and Suppression System. The 10.36-meter test chamber was used initially, prior to installation of the suppression system, to determine methods of initiation, firing procedures, dust/air ratios, instrument locations, and recording methods. After establishing these basic requirements and completing modifications to the chamber and systems to assure repeatable test criteria, the suppression system was installed. Six tests were conducted using the suppression system to suppress the dust fire/explosion, three using Halon 1301 and three using water as the suppressing agent.

The extinguishing agent was loaded first for all tests in which the suppression system was used. The explosive burst disc and holder were assembled and installed, and the tank was loaded with extinguishing fluid (6.8 kg of Halon 131 or 57 liters of water). The gallery dust nozzles were removed and paper diaphragms were installed in the base. Each nozzle was loaded with 50 grams of sulfur and then reinstalled in the chamber. The M43 flare ignitor was prepared and mounted, then the gallery was closed and sealed. The gas manifold was pressurized to 758 kilopascals (kPa) (110 psi) with compressed air and the extinguisher tank was pressurized to 4140 kPa (for Halon) or 2070 kPa (for water) with nitrogen. The initiator for the burst disc valve and the flare ignitor were then connected.

The flare was ignited by the range sequencer, and two seconds later the air valves opened so that dust was injected into the chamber. Action of the UV sensor and burst disc valve then followed automatically.

Visual evidence of propagation was provided by posttest inspection and by observing the motion pictures. The limit of flame advance from passive sensors, timing of ignitor, dust injection time, extinguisher injection time, pressure traces, photocell outputs and the UV sensor signal were recorded.

4.0 RESULTS AND DISCUSSION

4.1 Glass Tube Hartmann Apparatus. Using sulfur as the sample material, good dispersion of the dust in the tube was obtained during 8 of 12 tests. Tests run with a continuous flow of air at 103-140 kPa (15-20 psi) using 0.15 gm of sulfur resulted in even dust cloud distribution throughout the tube in 2-3 seconds. The average density of sulfur in the tube under these conditions was about 0.02 gm/liter.

4.2 Steel Tube Hartmann Apparatus. Observations made using the mirror clearly showed the progr-ss of the fireball up the tube. The dust initially produced a haze above the fireball, and was blown out the end of the tube as the fireball approached the exit. Matches placed along the tube interior failed to ignite, but after each test small molten globules of sulfur coated the tube walls. Flame propagation throughout the length of the tube resulted for charge weights of 3-6 grams at an air pressure of 520-1040 kPa (75-150 psi). Improved

dust distribution was noted at the higher pressures. The fireball appears as a donut-shaped bright ring on one 500 frame per second movie that was made of the propagation. Timing information as indicated by the pressure, optical and temperature sensors are given in table 1. In all cases, the top pressure sensor either did not show a pressure trace or the signals were so erratic as to be unusable. The general form of the pressure traces showed an initial spike followed by a slow pressure rise.

TABLE 1. PRESSURE AND OPTICAL SENSOR DATA, HARTMANN APPARATUS

Trial Number	Time Between Sensors (ms)				
	Pressure 1-2	Optical 1-2	Optical 2-3	Temperature 1-2	Temperature 2-3
1	13.0	9.6	7.2	15.6	28.1
2	9.1	9.0	6.7	8.8	24.5
3	10.1	8.2	6.0	11.8	33.1
4	3.5*	9.4	5.1	9.0	13.3
5	1.6*	10.7	4.5	no data	19.8
6	11.8	12.4	5.1	9.1	21.8
7	2.8*	11.9	7.5	no data	19.2
8	4.3*	14.2	no data	no data	19.4
Average	11.0±1.7 *(3.0±1)	10.7±2.0	6.0±1.2	11 ±3	22±6

The time of arrival data was used to calculate average velocities of the pressure wave and flame front during propagation up the tube, results of which are given in table 2. In four of the eight tests a pressure wave velocity of approximately 250 m/sec was observed, compared to an average of 70 m/sec for the remaining trials. This is probably indicative of a low order detonation in the former case, compared to a low velocity burn during the latter runs; apparently the conditions for detonation were marginal during these tests. If the low-order pressure data is used, the correlation of velocities between sensor positions 1 and 2 (0.762 meters apart) is remarkable. On the other hand, between positions 2 and 3 the optical data shows an increasing front velocity whereas the thermal data shows a decrease. It is possible that the optical sensors triggered early due to reflections or other effects, or perhaps the thermocouples with inherent heat capacity may have taken longer to respond at position 3 as the fleeting flame front passed. The general indications from these experiments were that flame front propagation within the tube occurs with relative low velocity, accompanied or sometimes outrun by the pressure wave.

4.3 Dust Gallery and Suppression System. Visual examination of the gallery after successful test runs without the suppression system showed only small traces of unburned sulfur on the floor, with small globules of sulfur covering the walls and clouding the plexiglas face. In tests where propagation was incomplete, a definite demarcation between clouded and clear surfaces could be observed. The cotton ball passive sensors also clearly marked the limit

TABLE 2. REACTION PROPAGATION VELOCITIES, HARTMANN APPARATUS

Sensor Position	Average Velocity, m/sec		
	Pressure	Optical	Thermal
1-2	69+9 (250±70)	71±10	69±15
2-3	no data	127±20	35±8
1-3	no data	91±15	46±10

of flame advance. Examination of the Hulcher and high speed motion pictures showed initiation within about 0.1 seconds after injection of the dust in the chamber. The dust as it is discharged from each nozzle forms an overlapping circular pattern which shortly after ignition can be observed being swept toward the chamber exit under force of the compression wave built up ahead of the flame front. The flame, clearly visible at ignition, becomes obscure due to dust and smoke buildup, and is visible only in flashes as propagation occurs. Continuous burning is visible again at the exit of the chamber.

Data sheets containing measurements of pressure, ionization and optical data obtained during the tests with the suppression system in place are contained in Appendix A. Each pressure trace showed an initial peak due to the compression wave from the reaction, followed by a relatively slow rise during the time that the optical sensors and ion probes indicated presence of flame. Subsequently, each pressure trace showed a sharp peak which is attributed to passage of the suppressant along the transducer array. The photocell data was extremely erratic, and little conclusive information could be obtained from the traces. Apparently these units responded to the initial dust injection, the movements of the dust cloud as the pressure wave passed, and the passage of the suppressant fluid in addition to the flame front. The photocell data was disregarded during final analysis, and an average flame front velocity was obtained primarily from the reaction of the UV sensor. This was corroborated by the ion probe data that was obtained during four tests.

The timing versus distance curves in figures 20 through 25 provide a display of all significant events during these experiments. From the point of ignition (0.61 meters from the left end), a compression wave travels down the gallery at near sound velocity. This is followed by the much slower flame front which triggers the UV sensor. After an inherent delay of about 30 milliseconds, the suppressant is released from the right end and propagates back through the gallery at or above sound velocity. Intersection of the flame front with the suppressant propagation curve indicates the point where the fire would be extinguished if the system were 100 percent effective. Comparison of this point with the passive sensor indicators then provides an indication of the suppression effectiveness.

A summary of the data from the dust gallery tests is given in table 3. The reaction of the ultraviolet sensor and deluge valve to the flame front was remarkably consistent. Discounting one test, the total reaction time from detection to initiation of the deluge system was 28 ± 2 msec. For the Halon tests, figures 20 through 22, it is apparent that the suppression occurs with essentially no delay; the flame was extinguished within 0.5 meters and within 10 msec after the suppressant arrived. For the water tests, however, the suppressive action as well as the measurement system performed less satisfactorily. The flame appeared to

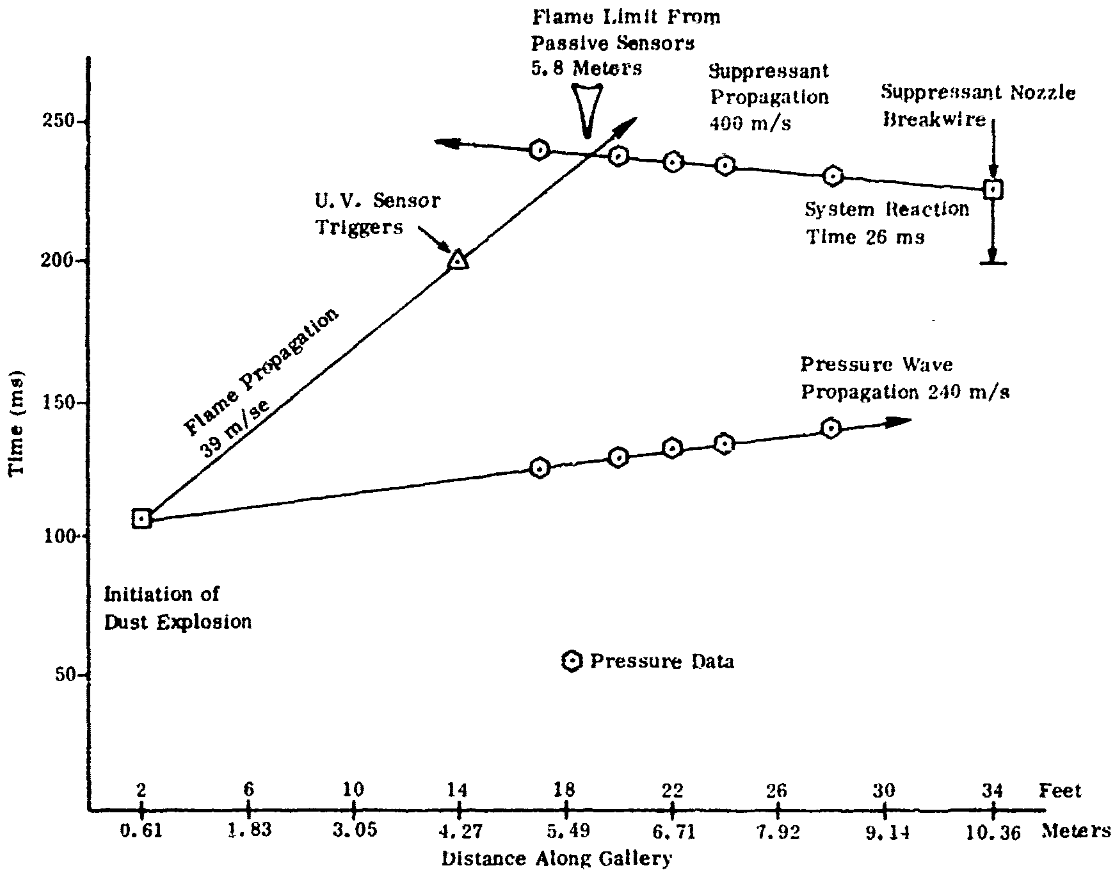


Figure 20. Test No. 40-5-01 Halon Suppressant

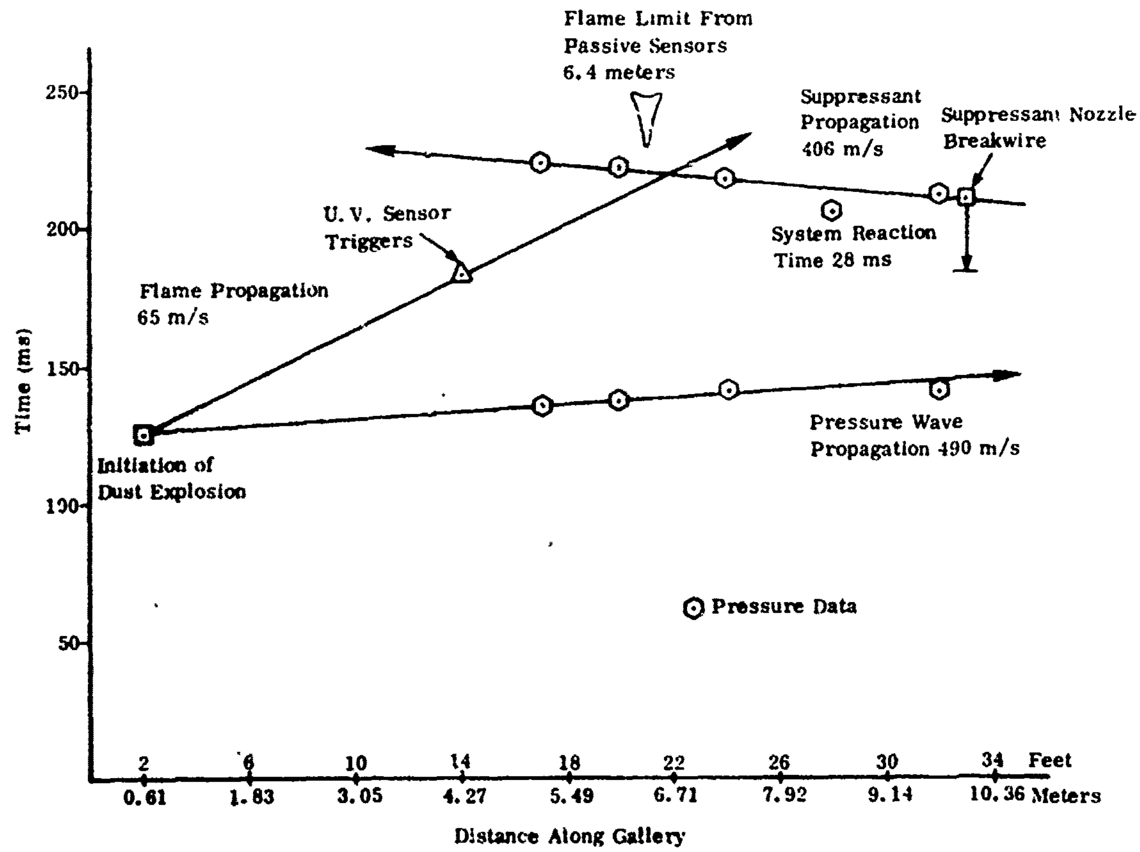


Figure 21. Test No. 41-5-01 Halon Suppressant

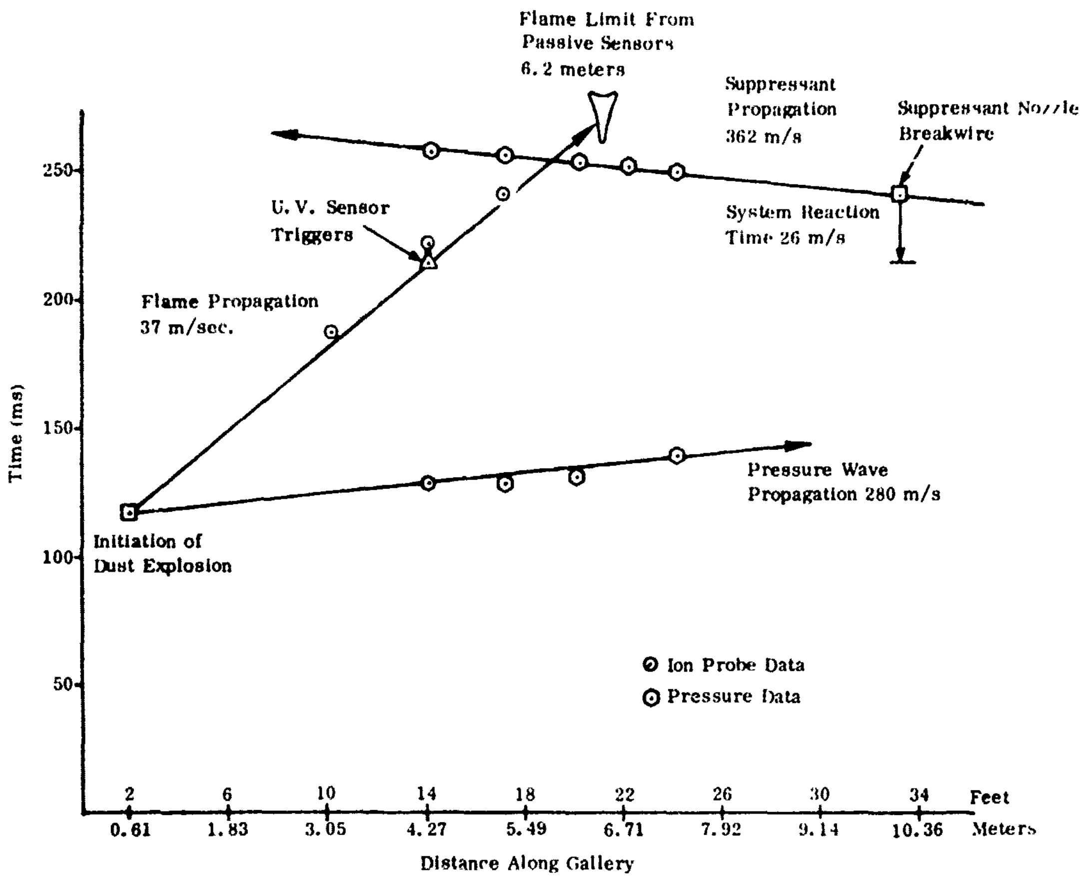


Figure 22. Test No. 47-5-01 Halon Suppressant

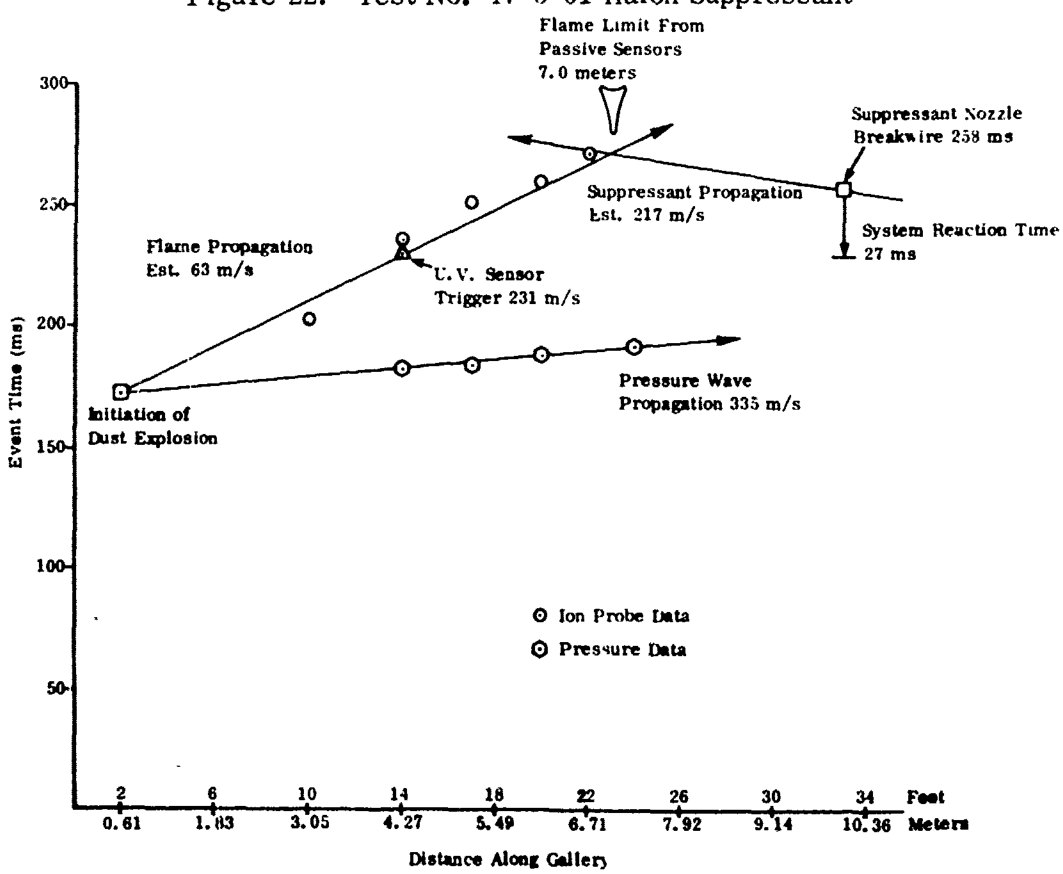


Figure 23. Test No. 48-5-01 Water Suppressant

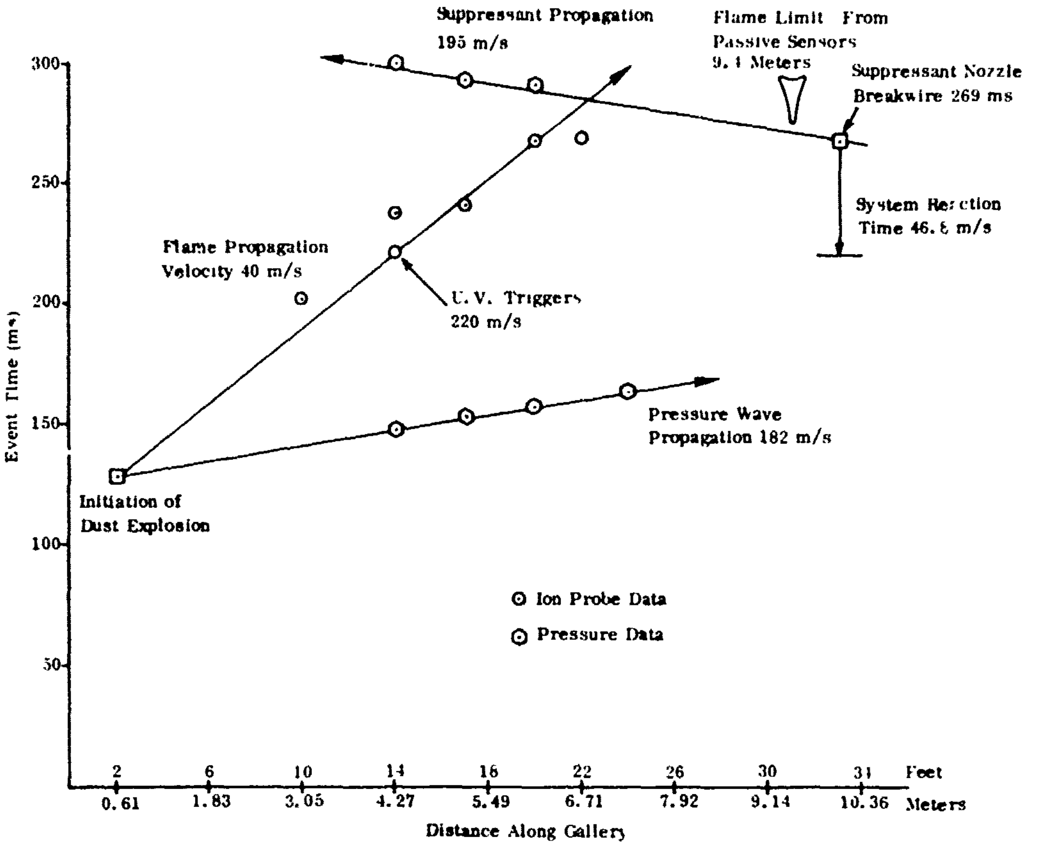


Figure 24. Test No. 49-5-01 Water Suppressant

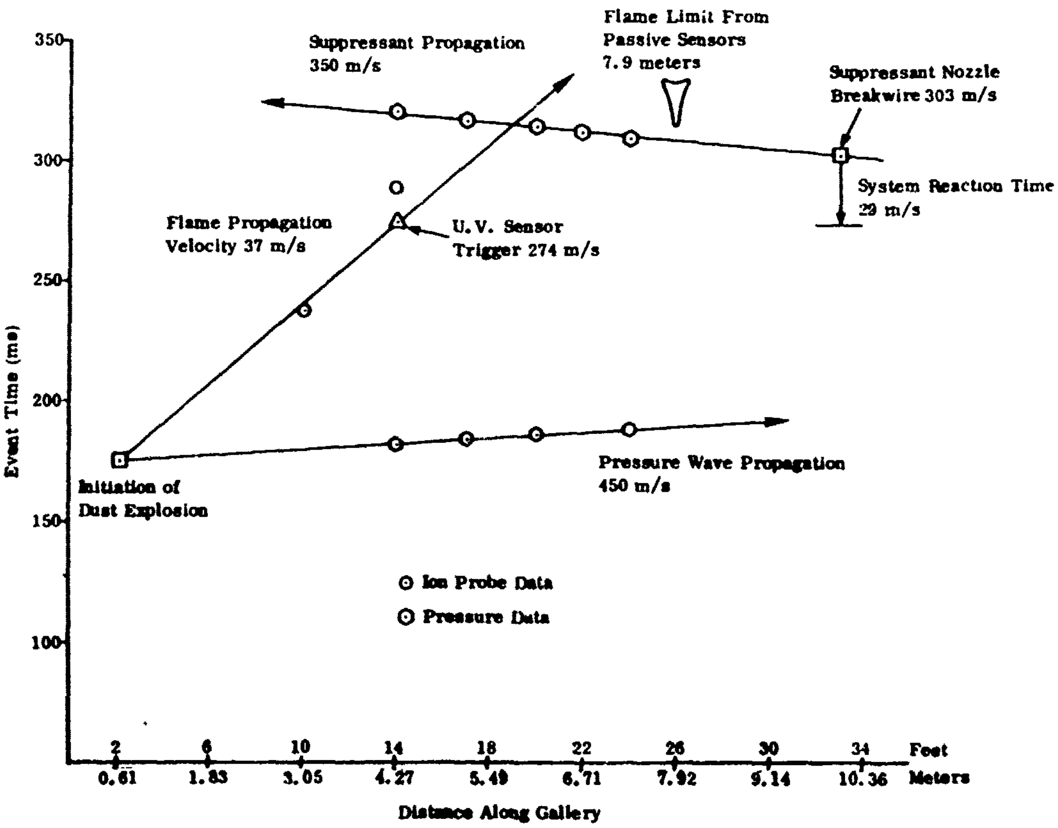


Figure 25. Test No. 49-5-02 Water Suppressant

TABLE 3. SUMMARY OF FIRE SUPPRESSION TEST DATA

Test No. and Fluid	Flame Arrival Time at U V Sensor Location 4.27m (ms)	Suppressant Injection in Chamber Time From Dust Nozzle Breakwire (ms)	System Reaction Time U V Sensor to Suppressant Injection (ms)	Flame Velocity Ion Probe Parameters (m/sec)	Fire Extinguish Point, Passive Sensor Location (m)	Max. Flame Static Pressure PSIG	Leading Edge Pressure Wave Velocity (m/sec)	COMMENTS
40-5-01 Halon	200	225	26.0		5.8	0.9	240	
41-5-01 Halon	182	210	28.0		6.4	0.8	190	
47-5-01 Halon	216.2	242.5	29.3	41	6.4	0.8	280	
48-5-01 Water	230.9	257.3	26.4	48	7.0	0.6	335	
49-5-01 Water	220.3	267.1	46.8	44	9.4	1.1	182	All the leaves or the burst disc sheared off and passed through the suppressant nozzle. Probably plugged nozzle initially.
49-5-02 Water	274	303.5	29.5		7.9	1.2	150	Suppressant nozzle plugged with pieces of burst disc approximately 80 percent restriction.

advance 2-3 meters beyond the suppressant-flame interaction, which translates into 60-80 ms in time. In all cases the flame was extinguished prior to exiting the gallery, but the superiority of the Halon 1301 as a suppressant was clearly established. However, the additional expense and environmental problems associated with the use of halogenated hydrocarbons may offset the enhanced performance.

In summary, the results of this test series indicate that a UV detector/high-pressure suppression system can be highly effective in controlling the extent of damage due to flame propagation within a pyrotechnic manufacturing facility. Depending on the application, a fire can either be extinguished at the source or confined to a limited area such as the cubicle in which an operation takes place.

5.0 CONCLUSIONS

5.1 Characteristics of Flame Propagation. Sulfur dispersions in air are subject to low-order detonation when ignited by a hot source. A compression wave propagates outward with near sonic velocity, followed by a much lower velocity flame front.

5.2 Suppression System. An ultraviolet-detector/high-pressure quench system with a burst deluge valve is sufficiently fast in action to detect and extinguish a sulfur dust deflagration within 20-100 milliseconds. Using similar systems, Halon 1301 is a better suppressant than water.

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APPENDIX

DATA SHEETS

DATA SHEET, TEST NO. 40-5-01

FUEL: Sulfur SUPPRESSANT: Halon

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time									Passive sensors showed burning 5.79 meters from ignition end of chamber
Photocell Signal Time			181	187	195			208	
First Compression Wave Arrival Time			124	128	132	134		140	
First Compression Wave Maximum Pressure, psig			.40	.40	.90	.75			
Suppressant Pressure Front Arrival Time			239	238	235	234		230	
U.V. Sensor Indication of Flame Arrival		200							

DATA SHEET, TEST NO. 41-5-01

FUEL: Sulfur SUPPRESSANT: Halon

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time									Passive sensors showed burning 6.40 meters from ignition end of chamber
Photocell Signal Time			170				163	182	
First Compression Wave Arrival Time			134	138		140		142	
First Compression Wave Maximum Pressure, psig			.5	.4		.8			
Suppressant Pressure Front Arrival Time			224	222		218		206	
U.V. Sensor Indication of Flame Arrival		182							

DATA SHEET, TEST NO. 47-5-01

FUEL: Sulfur SUPPRESSANT: Halon

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time	188	222	242	282		384	343	353	Passive sensors showed burning 6.40 meters from ignition end of chamber
Photocell Signal Time	192		240	261			258	259	
First Compression Wave Arrival Time		129	129	132		140			
First Compression Wave Maximum Pressure, psig		.60	.80	.40		.55			
Suppressant Pressure Front Arrival Time		258	256	254	252	251			
UV Sensor Indication of Flame Arrival		216.2							

DATA SHEET, TEST NO. 48-5-01

FUEL: Sulfur SUPPRESSANT: Water

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time	202.4	235.4	251	260.1	274.6	298.2	380	345.8	All the leaves of the burst disc sheared off and passed th ough the nozzle. Probable initial plugging accounts for long delay in nozzle breakwire
First Compression Wave Arrival		181	184	187		191			
First Compression Wave Pressure		0.6 psi	0.5 psi	0.5 psi		0.6 psi			

NOTE: Time reference lost on photo cell data and on pressure traces at 4.27 and 7.32 meter locations.

Start time reference for pressure curves at these locations estimated from curve through start time of pressure sensors located at 4.27 and 5.18 meter locations.

DATA SHEET, TEST NO. 49-5-01

FUEL: Sulfur SUPPRESSANT: Water

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time	201	237	240	267	269	297	314	332	Suppressant nozzle was 80 percent plugged with pieces of burst disc Passive sensors showed burning 9.45 meters from ignition end of chamber
Photocell Signal Time		236	250	266	270	279	290	320	
First Compression Wave Arrival Time		148	154	158	no data	163			
First Compression Wave Maximum Pressure, psig		1.1	0.85	0.7	no data	0.8			
U.V. Sensor Indication of Flame Arrival									

DATA SHEET, TEST NO. 49-5-02

FUEL: Sulfur SUPPRESSANT: Water

PARAMETER IDENTIFICATION (TIMES IN ms)	INSTRUMENT LOCATION IN METERS FROM IGNITION END OF CHAMBER								
	3.05	4.27	5.18	6.09	6.71	7.32	7.92	8.53	COMMENTS
Ion Probe Signal Time	238	288	325	343					Passive sensors showed burning 9.45 meters from ignition end of chamber
Photocell Signal Time	282		322	359	399				
First Compression Wave Arrival Time		181	185	195		188.5			
First Compression Wave Maximum Pressure, psig		.25	.75	.44		1.1			
Suppressant Pressure Front Arrival Time		320	317	314	312	310			
U.V. Sensor Indication of Flame Arrival		274							

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